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OPEN CYCLE FUEL CELL POWER PLANT DIRECT  
CURRENTS, 1.5 KW

O. J. Adlhart, et al

Engelhard Minerals and Chemicals Corporation

Prepared for:

Army Mobility Equipment Research and  
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July 1973

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OPEN CYCLE FUEL CELL POWER PLANT

DIRECT CURRENT, 1.5 KW (U)

FINAL TECHNICAL REPORT

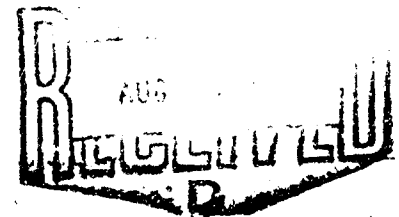
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U.S. Army Mobility Equipment  
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Contract DAAK02-70-C-0517

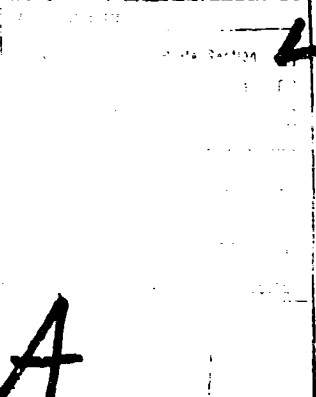

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## Summary

Under this program an advanced development model of a portable field electrical power source capable of operation on logistic military fuels was designed. The design was based on and substantiated by full size breadboard testing conducted concurrent with the design effort.

The 1.5 KW Open Cycle Power Plant design is shown in Fig. 1. The design was comprised of three basic subsystems: Thermal Cracker, Fuel Cell and Power Conditioner, and Control Module. The thermal cracker serves to convert logistic military hydrocarbon fuels to a hydrogen-rich gas stream. The hydrogen in this stream is electrochemically combined, within the fuel cell, with oxygen from ambient air to produce electrical power. The power conditioner and control module regulates the raw electrical output of the fuel cell and provides control functions for the thermal cracker and fuel cell.

The design of the 1.5 KW power plant was verified by the operation of a full scale breadboard system consisting of thermal cracker, fuel cell, and control module. The power conditioner was not tested in breadboard form. The switching transistor and drive circuitry, however, were tested on fuel cell output.

Full scale breadboard testing of the integrated system was limited to 21 hours during which the system produced 1.25 KW at a fuel rate of 2.5 lbs/hr of JP-4. The thermal cracker subsystem was operated for a total of 80 hrs. Due to this limited period of operation it is recommended that further investigation of life effects be conducted before proceeding with construction of the advanced development model power source.

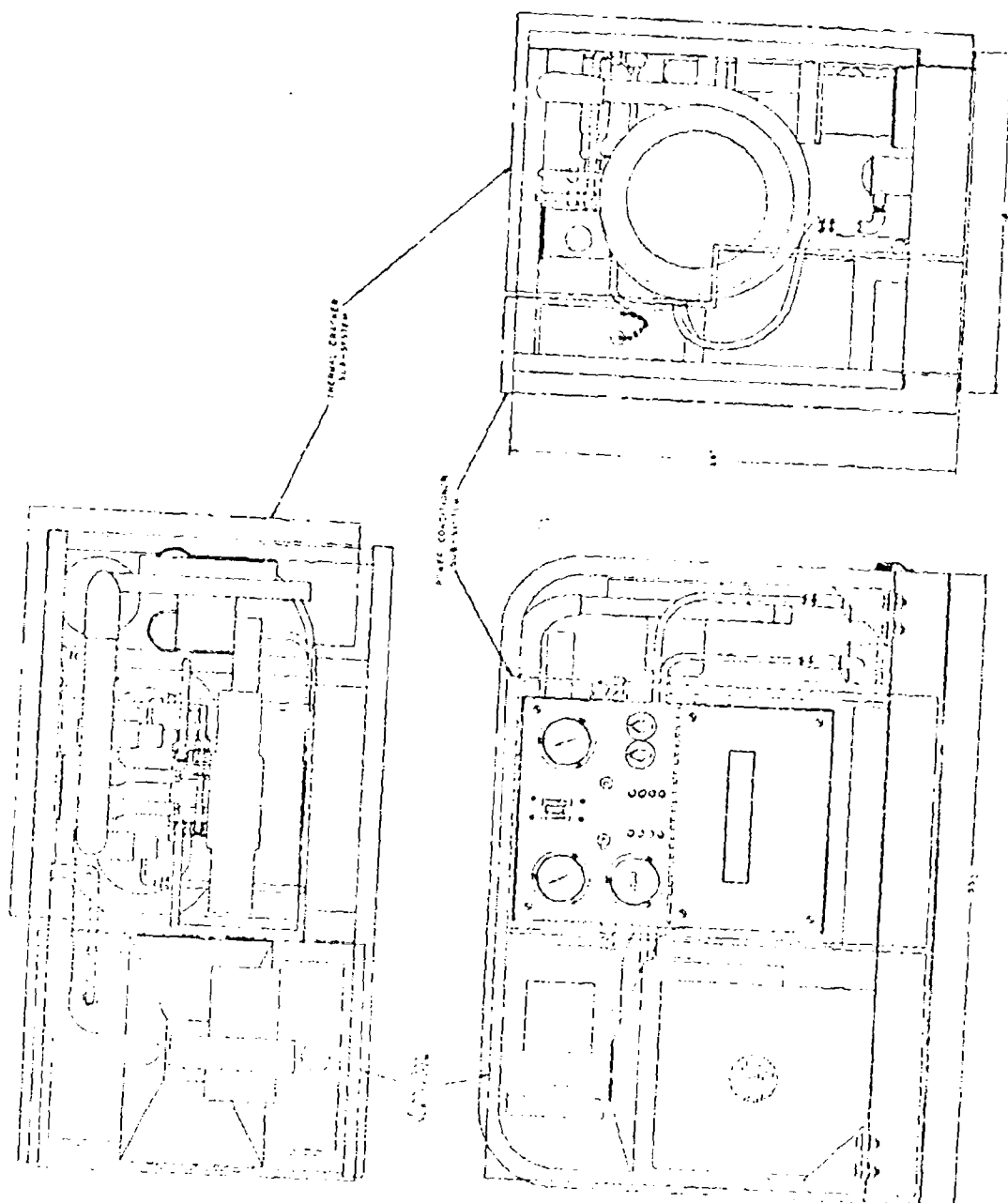


FIG. 1

## Forward

This is the final report on the work done in Phase I of a program to develop a family of field power supplies based on the open cycle fuel cell process. The report covers the technical work performed from July 1, 1970 through April 30, 1971. During Phase I, a design and development program on a 1.5 KW Power Plant was conducted.

This report was prepared by the Engelhard Industries Division of Engelhard Minerals & Chemicals Corporation in accordance with the provisions of Contract No. DAAK02-70-C-0517, for the U. S. Army Mobility Equipment Command, Research and Development Center, Fort Belvoir, Virginia.

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The work was performed in both the Research & Development Department and Systems Department of Engelhard Industries.

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### 3.0 Introduction

The objective of this program was to design a field power source capable of converting commonly available, military hydrocarbon fuels into electrical power.

The 1.5 KW, open cycle, fuel cell power plant designed under this contract is shown in Figure 2. The design consists of three major subsystems: Regenerative thermal cracker, phosphoric acid fuel cell, and power conditioner and control module.

The thermal cracker serves to crack the fuel into its constituent hydrogen and carbon, the hydrogen being released as a gas and the carbon being deposited in solid form within the cracking chamber. Periodically the cracking chamber is regenerated to eliminate built-up carbon and provide reaction energy by combustion of the carbon with air. In order to provide a continuous flow of hydrogen, two reactors were incorporated in the 1.5 KW system design, sequenced so that while one reactor is cracking, the other is being regenerated.

Electrical power is produced by the fuel cell by the electrochemical combination of hydrogen and oxygen to form water. The fuel cell design used in this program utilizes an immobilized phosphoric acid electrolyte and platinum activated electrodes. Regulation of the raw DC power from the fuel cell and process control is provided by the power conditioner and control module.

Effort on this program was conducted in four simultaneous phases: Fuel conditioner, fuel cell, power conditioner and systems integration. The first three phases were conducted independently. Systems integration utilized data received from the other three phases to develop the process control system and the final packaged design. Due to the high level of development required, principal effort was concentrated on the development of the thermal cracker sub-system. The 1.5 KW Advanced Development Model design was supported by laboratory testing of individual critical components and by the operation of a full scale breadboard fuel cell - thermal cracker system.

This program was supported by previous and concurrent fuel cell and thermal cracker development performed by Engelhard and MERDC.

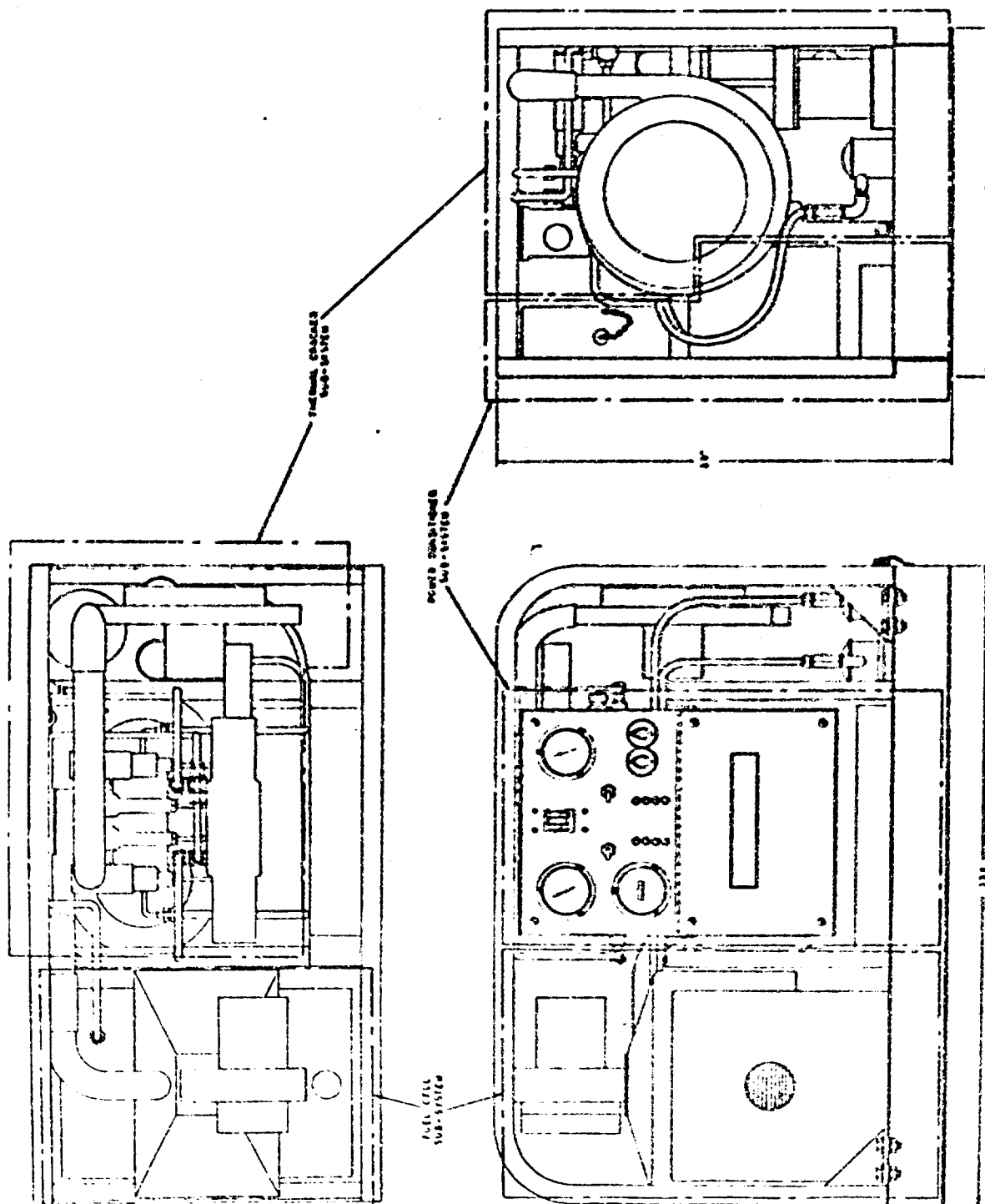


FIG. 2

#### 4.1 Fuel Cell Subsystem

The fuel cell subsystem serves to electrochemically combine hydrogen, from the thermal cracker, with oxygen, from ambient air, to produce DC electrical power and water. The fuel cell used in this program and specified in the advanced development model design is based on the Engelhard, air-cooled, matrix type, phosphoric acid fuel cell design. The basic cell employs an immobilized phosphoric acid electrolyte and platinum activated electrodes.

##### 4.1.1 General Design Features of Fuel Cell Subsystem

The prototype fuel cell employed in the development program is shown in Fig. 3 and 4. The system consists of the fuel cell stack with an integral air supply, a temperature control system and a start-up heat exchanger. This system was developed under a concurrent contract, DAAK02-68-C-00407.

The components are housed in two deep drawn, aluminum shells butting on the top plate of the stack. This plate, of cast aluminum, also provides a mounting surface for the auxiliary components. The top cover is spring loaded against two toggle latch closures. Releasing the latches allows the top cover to raise, exposing an annular circumferential opening through which ambient air is drawn for cell operation.

##### 4.1.1.1 Fuel Cell Stack

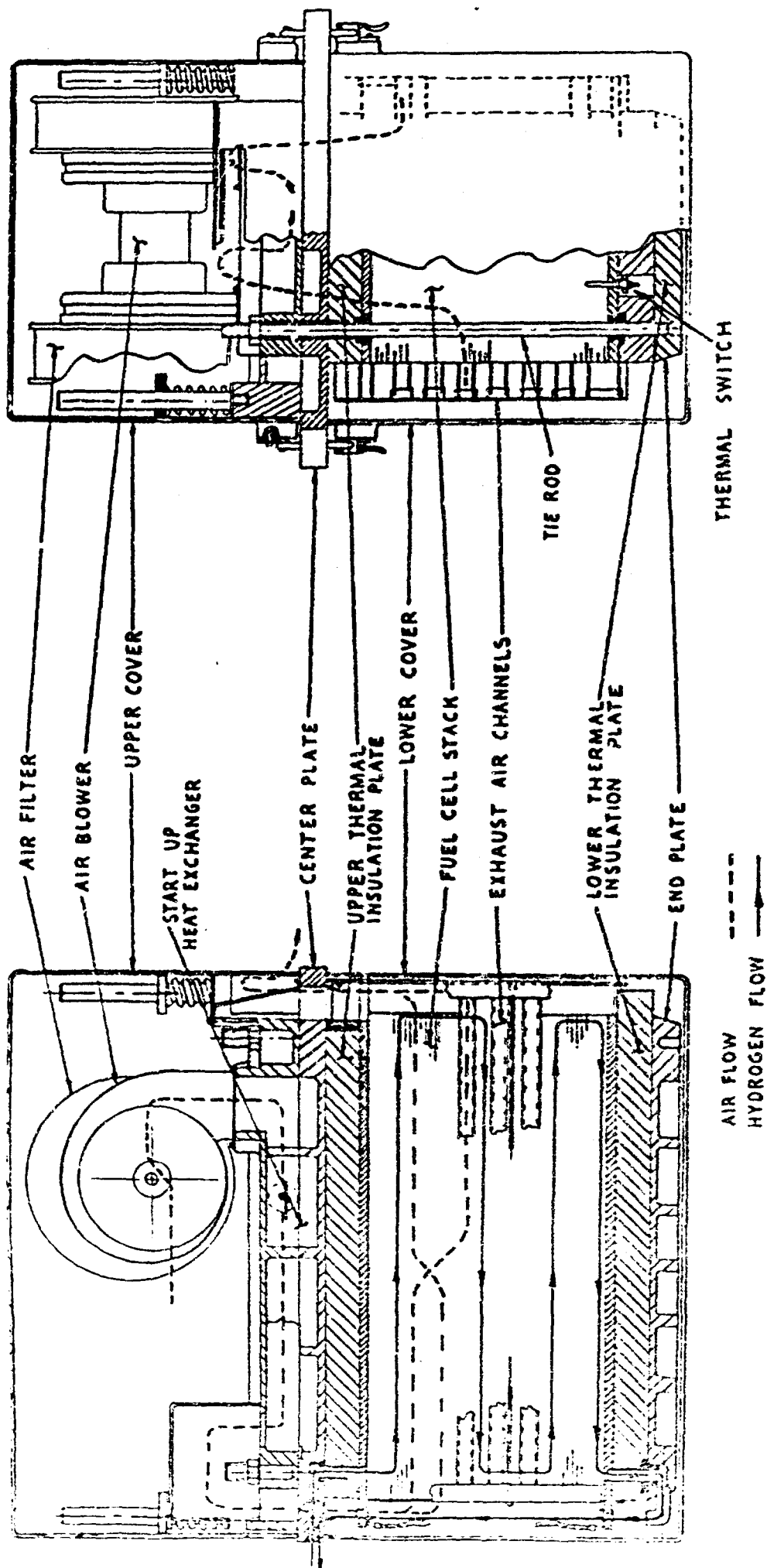
The fuel cell stack employed in the breadboard system is of the conventional bipolar construction and is made up of a total of 42 single cell modules.

The basic cell assembly or module consists of an electrode-matrix laminate, bipolar plate, anode support shim, cathode support shim, spacer, and gasket.

The performance and physical characteristics of the electrode-matrix laminate have been covered in previous reports (references 2, 3, 4, 5, 7, & 8).

The bipolar plates provide current collection, reactant manifolding and support for perimeter gasketing. These plates are fabricated from 1/8" thick aluminum and are gold





PROTOTYPE FUEL CELL ASSEMBLY  
FIG. 3

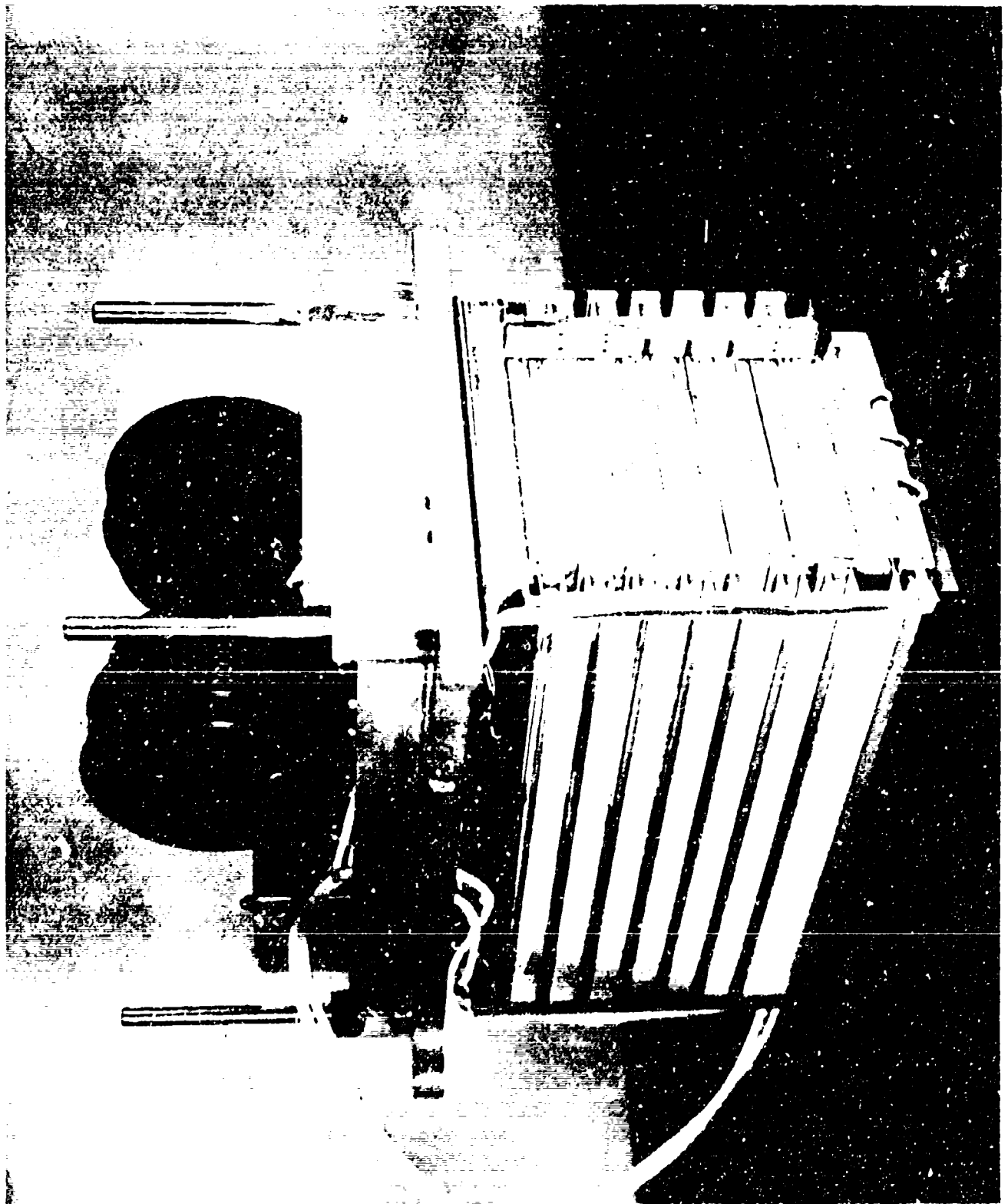


FIG. 4

Prototype Fuel Cell Assembly  
With Protective Covers Removed.

#### 4.1.1.1 Cont.

plated for protection against corrosion. Anode and cathode shims are used to prevent the sealing edges of the cell laminate and the gasket from pressing into the reactant flow grooves of the bipolar plates at the reactant inlet and outlets. These shims are 0.003" thick and gold plated for corrosion resistance. The gasket material is an ethylene-propylene formulation, originally developed at Fort Belvoir.

The fuel cell stack is contained between the end and thermal insulation plates in a filter press type assembly. Components required to make electrical, reactant and control connection to the stack are an integral part of this assembly.

The tie rods, to reduce space requirements, are not external to the stack but are positioned in the hydrogen manifold.

Both reactants pass through the stack in a single pass. To obtain high hydrogen utilization, the fuel is fed through the stack in a cascading path passing from the top to the bottom of the stack through groups of cells manifolded in series. The air enters the stack from both sides through exposed cathode grooves.

#### 4.1.1.2 Air Supply & Waste Heat Management

A single air stream is used to accomplish heat and water removal and to provide chemical air. This air flow is varied depending on ambient conditions and stack load to maintain a constant stack temperature. This mode of temperature control is possible since the air flow required for waste heat removal is greatly in excess of that needed for the electrochemical operation and water removal (6).

The fuel cell stack temperature is controlled by varying the air flow in response to the heat removal requirement. The air flow rate is controlled by a two-speed blower operating in response to a thermal switch sensing stack temperature. Two additional thermal switches are used for low temperature and over-temperature protection. At low temperatures ( $<200^{\circ}\text{F}$ ) removal of product water is insufficient and at high temperature ( $>300^{\circ}\text{F}$ ) degradation of the fuel cell

#### 4.1.1.2 Cont.

catalyst increases rapidly.

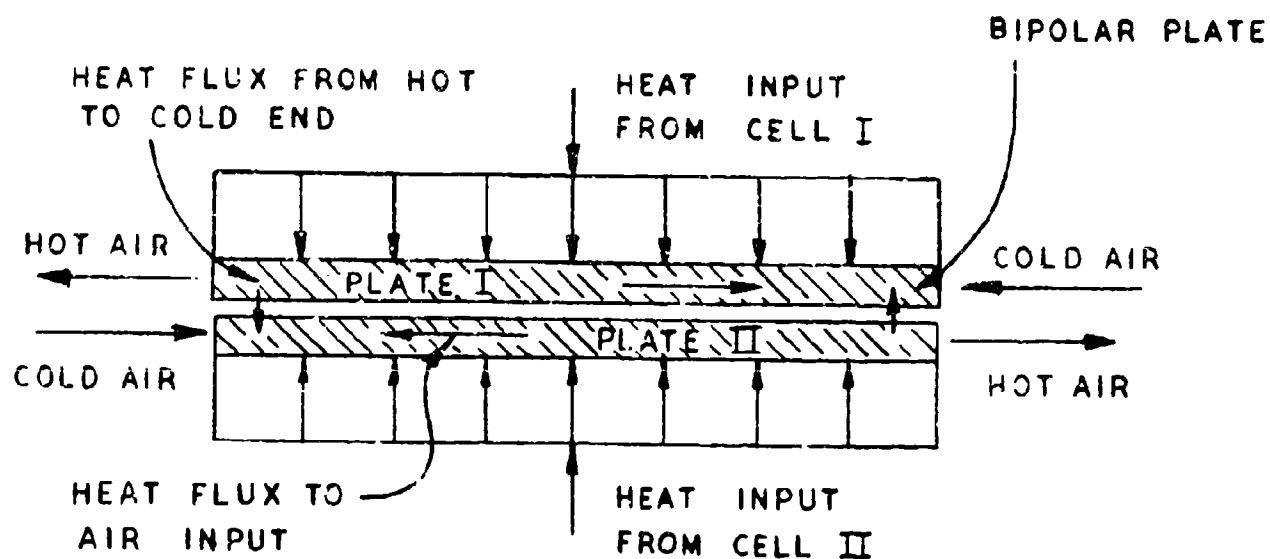
Temperature uniformity over the active cell area is a necessity for long cell life. Admitting the ambient air directly to the cathode cavities leads to a thermal gradient which is only counteracted by the thermal conductivity within the cell module.

The Alternate Flow Air Cooling Principle serves to minimize this gradient by utilizing the thermal conduction perpendicular to the air flow as indicated in Fig. 5. Air is admitted by a suitable manifolding to groups of three cells each from opposing sides of the fuel cell stack. The effect is that the cold region where air enters is adjoined by the hot ends of the bipolar plate where the air leaves the stack. Thermal conduction in the vertical direction provides a short path for heat transfer.

#### 4.1.1.3 Fuel Cell Start-Up Facilities

Although operable at most ambient temperatures some preheating of the phosphoric acid cell is desirable during start-up to minimize water accumulation in the electrolyte matrix. A suitable heat source for the start-up is the flue gas from the start-up cracker burner. In order to protect the fuel cell from damage due to local overheating by the widely varying flue gas temperature or poisoning by contaminants such as lead or sulfur, a heat exchanger is employed in the advanced development model design.

Start-up procedures are discussed in greater detail in Section 4.4.2.



# AIR FLOW IN ALTERNATE FLOW COOLING

FIG. 5

#### 4.1.2 Performance Characteristics of Prototype System

##### 4.1.2.1 Electrical Performance and Fuel Consumption

Current-potential characteristics and fuel consumption of the prototype system are illustrated in Fig. 6. Measurements were performed using a bottled fuel mixture containing 80%  $H_2$ , 19%  $N_2$  and 1%  $CO$ . At a stack current of 65 amperes, hydrogen utilization was 91%. The fuel loss is due to cross leakage and the power consumption of the air blower. The efficiency maximum of 41% is reached at approximately 30 amperes at lower currents efficiency decreases significantly as cross leakage causes a proportionately higher fuel loss.

Data shown in Fig. 6 refer to actual hydrogen consumed and do not include the fuel lost in the fuel cell bleed gas. The bleed requirements are largely a function of the carbon monoxide content. The effect of carbon monoxide on hydrogen utilization has been reported on earlier (7).

##### 4.1.2.2 Temperature Distribution and Air Pressure Drop in Breadboard Fuel Cell System

The cooling capacity of the breadboard fuel cell system was insufficient for sustained operation at the 1.75 KW operating point due to unwanted preheat of the cooling air within the stack casing, and excessive air pressure drop within the system. The highest output at which a thermal balance was maintained was 1330 watts net. Data recorded at this operating point are presented in Fig. 7. Inlet air was preheated by approximately 33°F through heat exchange with stack components prior to entering the fuel cell stack. Cooling air pressure drop data are summarized in Table 1.

The fuel cell stack was the major flow restriction. Most other components including the integral start-up heat exchanger employed in the breadboard fuel cell, materially added to the overall flow restriction.

TABLE I

Air Pressure Drop in Breadboard Fuel Cell

Fuel Cell Load	1,330 watts	1,690 watts
Estimated Air Flow	18 cfm	45 cfm

Pressure Drop/Inch H<sub>2</sub>O

Air Filter	0.30	-
Heat Exchanger	0.43	-
Passage Through Casting	0.21	-
Stack	2.45	3.50
Air Exhaust Channel	0.15	1.05
Air Exhaust Port	<u>0.15</u>	<u>0.45</u>
	3.69	5.00

Temperature distribution within the stack was acceptably uniform. The maximum temperature variation observed within an individual cell was 18°F. Higher cell to cell gradients were observed, however, cell to cell gradients are acceptable as they do not produce current density gradients within the stack.

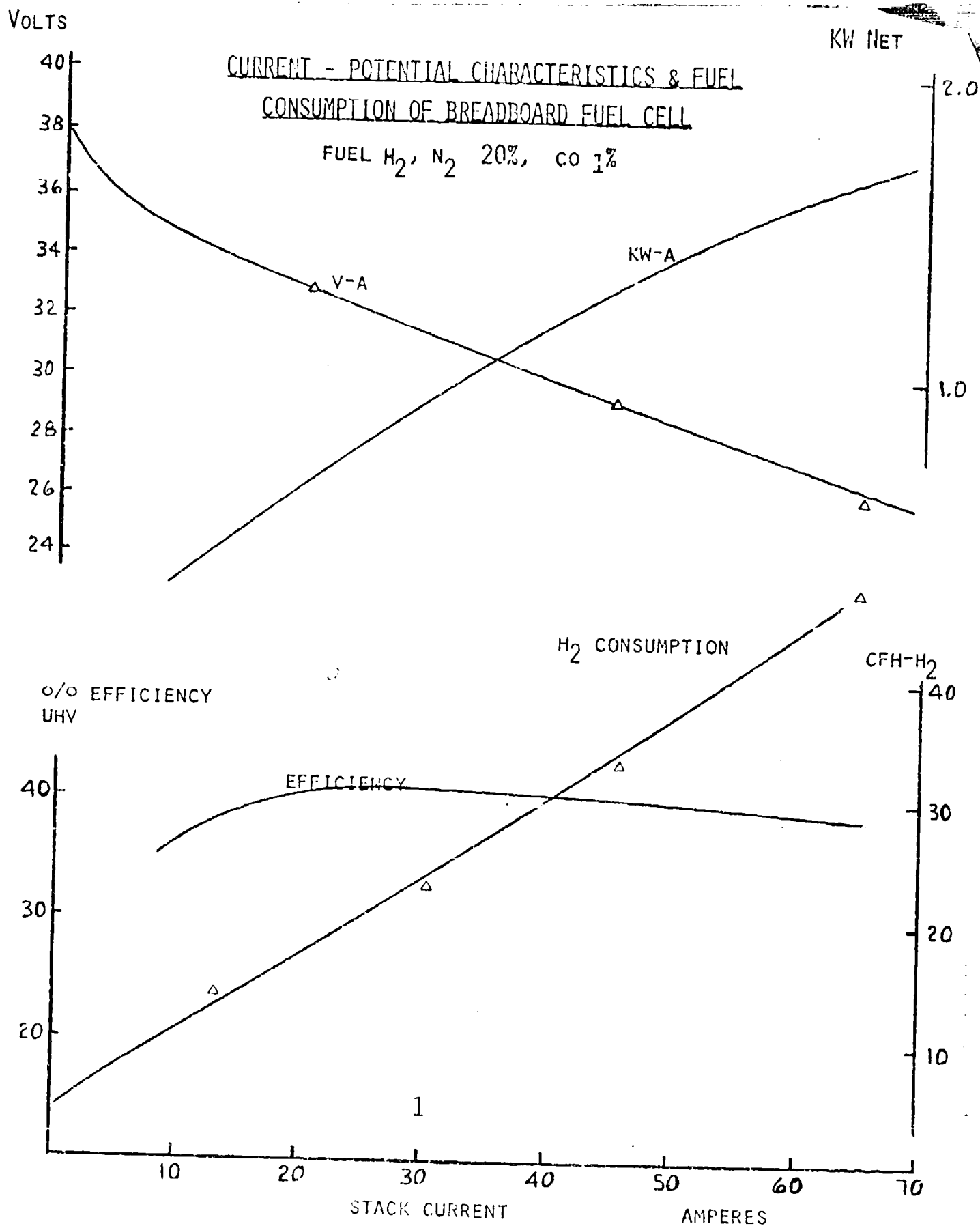
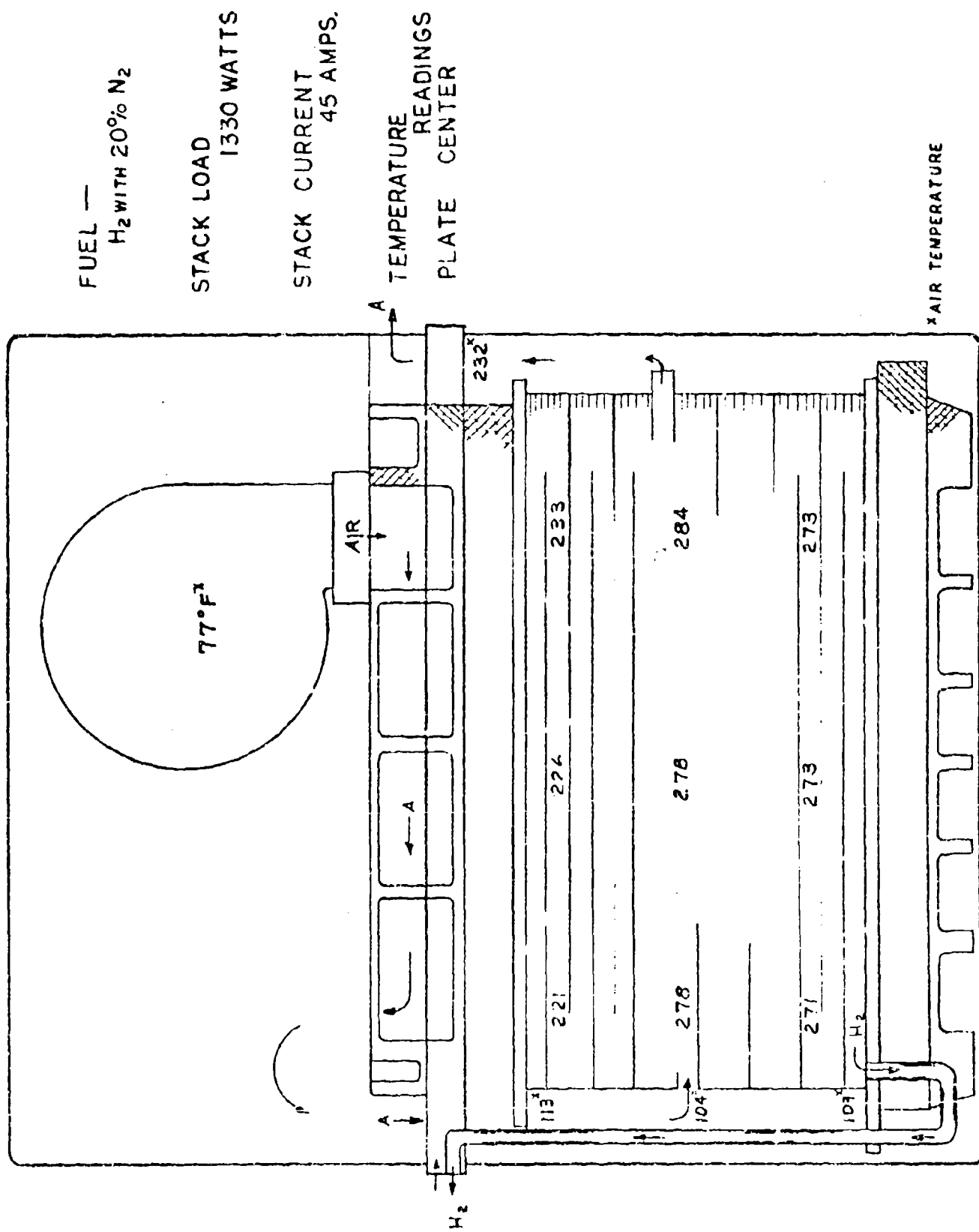


FIG. 6





TEMPERATURE DISTRIBUTION IN BREADBOARD FUEL CELL

FIG. 7

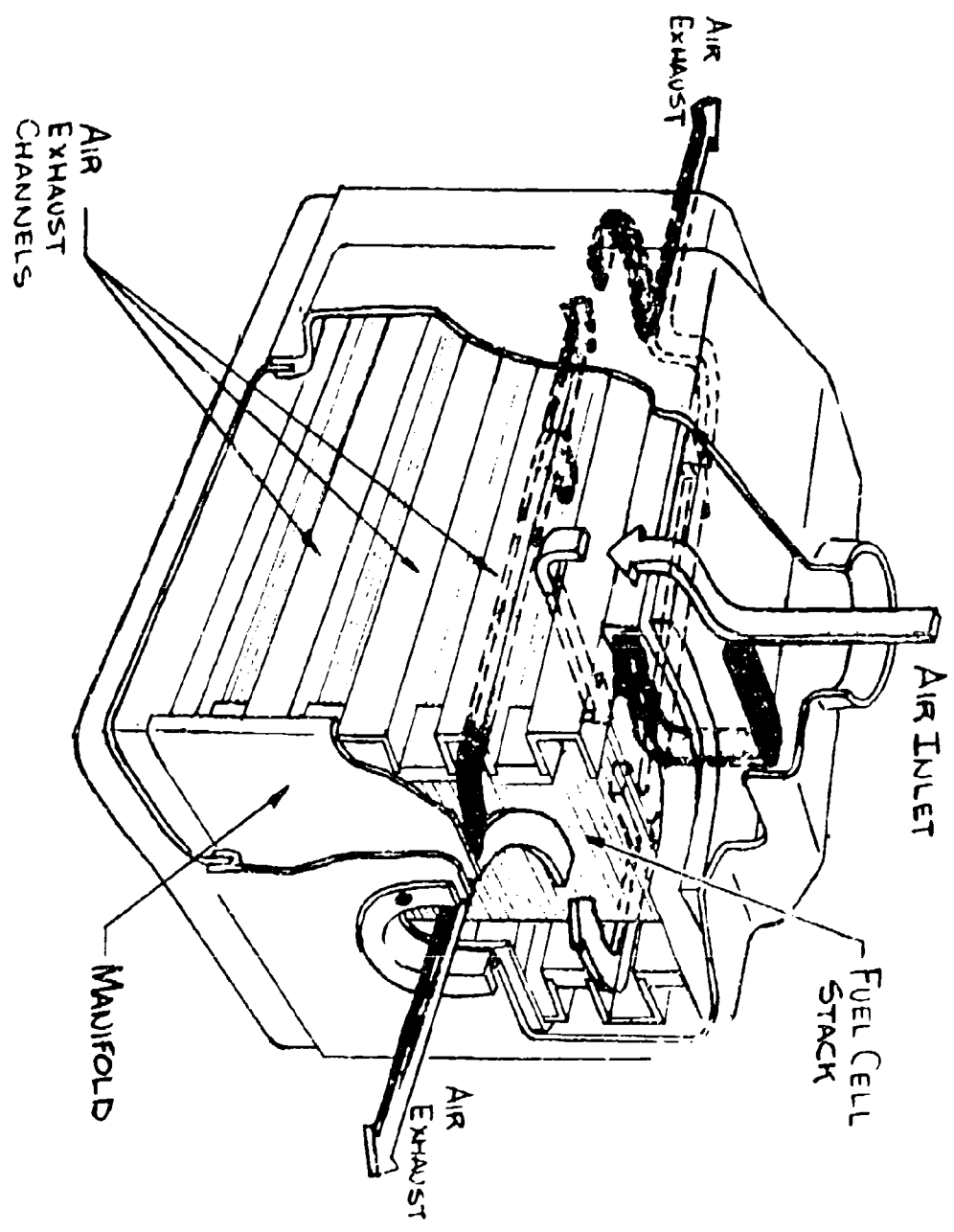
#### 4.1.3 General Features of Revised Fuel Cell Subsystem Design

A major deficiency of the prototype fuel cell subsystem discussed in Section 4.1.1 - 4.1.2 was caused by insufficient heat removal capability. The specific routing of the cooling air and system packaging are cause for excessive pressure drop and excessive preheating of the cooling air.

Fig. 8 illustrates schematically the design changes incorporated in the advanced development model design to correct this problem. In order to simplify air routing the blower and start-up heat exchange element are positioned external to the fuel cell unit. The configuration shown gives a balanced symmetrical flow with lower pressure drop. Exhaust air is directed out of both ends of the unit at right angles to the air flow in the stack. A housing contour matching the air routing serves to minimize the pressure drop.

Reinforced plastics are used for the housing and some internal structures to minimize internal heat exchange.

1.75 KW FUEL CELL SUB-SYSTEM CUT-AWAY



#### 4.1.4 Component Improvement Study

##### 4.1.4.1 Carbon Bipolar Plates

A major cost item in the fuel cell stack is the aluminum bipolar plate largely because of the required protective gold plating. A considerable effort was undertaken to replace these structures with comparable but less expensive carbon-based plates. Several experimental stacks were evaluated under this program. These stacks were partly available from concurrent studies (4).

Carbon poses a number of problems compared to metallic plates. Residual porosity and increased contact resistance between the collector plates and the metallized teflon electrodes require specific processing. Further, a critical consideration is its lower thermal conductivity since thermal conduction of the bipolar plate is relied upon for temperature distribution in the stack. The co-efficient of thermal conductivity of commercially available carbon plates range from 50-500 Btu/hr/ft<sup>2</sup>/°F/inch, as compared to 1558 for 6061 aluminum.

Pertinent data for commercially available carbon materials used for bipolar plate fabrication are summarized in Table 2, together with comparative data for 6061 aluminum.

TABLE 2

##### Materials Used for Fabrication of Bipolar Plates

Grade	Density g/cm <sup>3</sup>	Porosity** %	Thermal Conductivity Btu/hr/ft <sup>2</sup> /°F/in.	Electrical Resistivity l.ch
L-56*	1.63	20	250	0.0012
P-29*	1.85	0.8	70-100	0.0020
P3-W*	1.60	17	500	0.0005
Al 6061	2.70	---	1558	-----

\*Pure Carbon Co., St. Mary's, Pa.

\*\*Prior to impregnation.

#### 4.1.4.1 Cont.

Dimensional details and design features of test stacks with carbon bipolar plates are given in Table 3. L-56 Carbon was used exclusively.

TABLE 3

Test Stacks with Carbon Bipolar Plates

<u>Stack</u>	<u>Number of Cells</u>	<u>Plate Thickness</u>	<u>Number of Baffles</u>
C-1	15	1/8	None
C-2	42	3/16	5
C-3*	22	1/8	3

Plate Dimensions - 5-3/4 x 11-3/4

Active Area - 8-1/2 x 4-1/2

All stacks use the alternate flow air cooling principle with a manifolding frequency every third plate.

\*10 & 20 plate 1/4" copper.

---

The lower thermal conductivity of carbon has comparatively little effect on the thermal flux from cell to cell because of the short path and large cross-sectional area available for heat transfer. In the vertical direction, thermal conduction of the cell unit rather than the bipolar plate determines the effective co-efficient of thermal conduction.\*

The vertical temperature differentials observed in stack C-2 (Table 4) are illustrated in Fig. 9. This stack was

\*Reference is made to work performed under Ct. DAAK02-68-C-0407. The vertical coefficient of thermal conduction with alum.bipolar plates was determined as 19.2 watts/°C/cell as compared to 800 watts/°C/Cell for aluminum alone. Replacement of aluminum with L-56 carbon reduced the coefficient only to 17.6 w/°C/cell.

TEMPERATURE DISTRIBUTION IN STACK CONTAINER  
(STACK C-2)

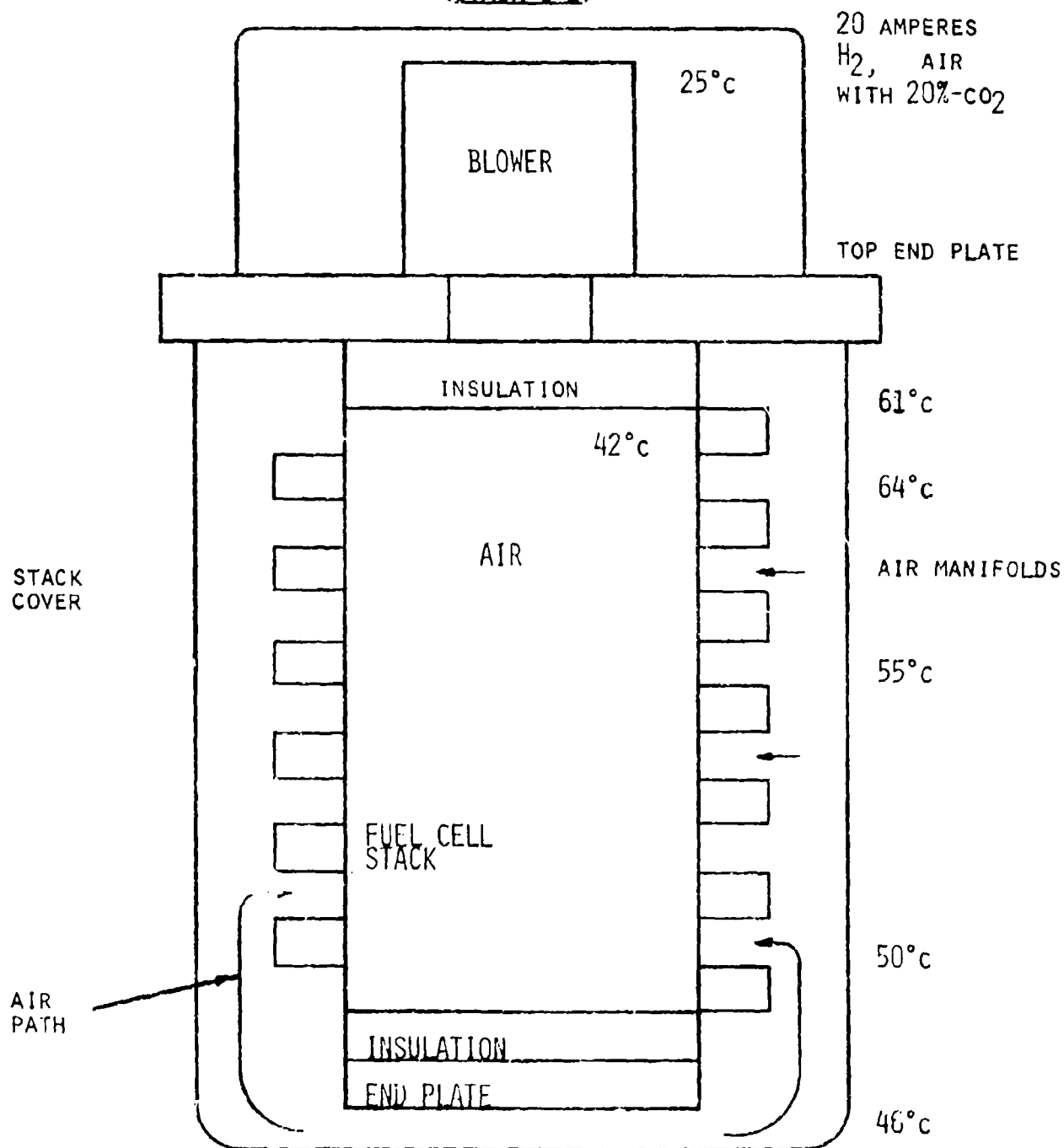


FIG. 9

#### 4.1.4.1 Cont.

operated and tested with an integral air supply and temperature control system. Temperature readings indicated in Fig. 10 refer to the center of the active cell area (see Table 3). A differential of  $31^{\circ}\text{C}$  develops between the hottest cell and the last and coldest cell in the stack. The temperature gradient is the result of heat losses through the end plates and preheating of the air prior to its entering of the fuel cell stack. The latter is illustrated in Fig. 8. The air temperature is shown at various points in the stack container. The cooling air rises from the bottom of the stack and preheats on the air exhaust manifolds before entering the fuel cell.

The thermal conductivity in the horizontal direction is largely dependent on the properties of the bipolar plate. Although the heat flux is small, differentials in temperature are magnified by the resulting current density gradients.

Test data for stack C-1 are tabulated in Table 4. Perpendicular to the air flow temperature differentials range from  $30\text{--}50^{\circ}$  between cell center and points near the hydrogen manifold (compare point 4 with 2 or 8). This large gradient develops as a result of heat losses from the hydrogen manifold.

In the direction of air flow, gradients are smaller, ranging from  $4\text{--}12^{\circ}\text{C}$  as the alternate flow air manifolding minimizes the effect of the cold ambient air entering the stack. (Compare points 1-2-3, 4-5-6, and 7-8-9).

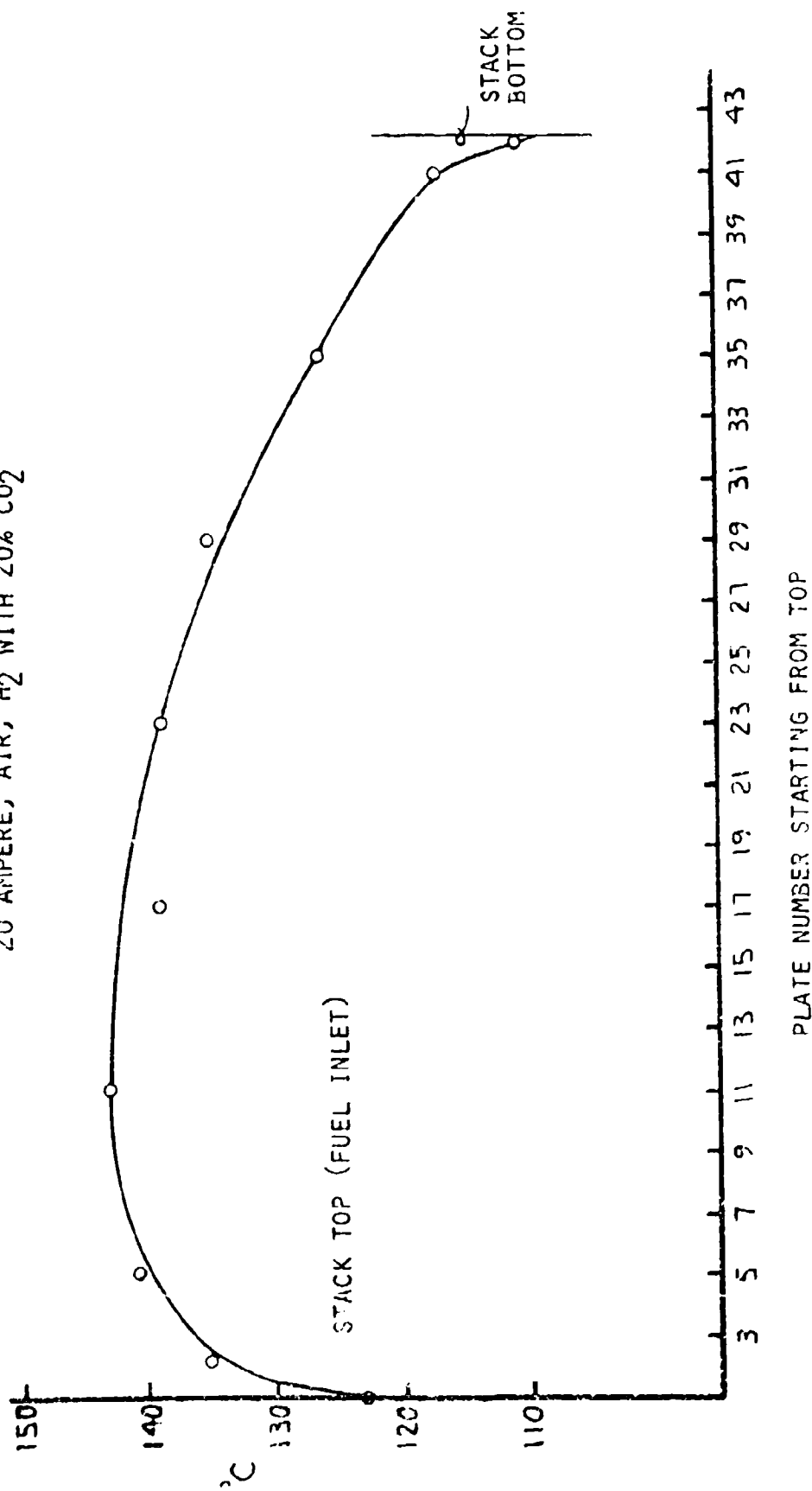
The insertion of metal plates materially reduces the temperature differential between the stack center and the hydrogen manifold.

In stack C-3, copper plates ( $1/4''$ ) were inserted every 10th plate. Test data are summarized in Table 5. Over the major portion of the stack temperature varies only by  $10^{\circ}\text{C}$ . Contrary to stack C-2, consistently higher temperatures were recorded in stack C-3 on one side of the hydrogen manifold. This is related to the specific mode of testing. In stack C-3 air was drawn through the fuel cell system by application of a vacuum to the air exhaust manifold. This had the effect of admitting air uniformly to the stack without cooling the sides of the stack. Stack C-1 was tested in a pressurized housing

VERTICAL TEMPERATURE PROFILE THROUGH

TEST STACK C - 2 (TABLE 4)

20 AMPERE, AIR, H<sub>2</sub> WITH 20% CO<sub>2</sub>





# TEMPERATURE DISTRIBUTION WITHIN CARBON STACKS

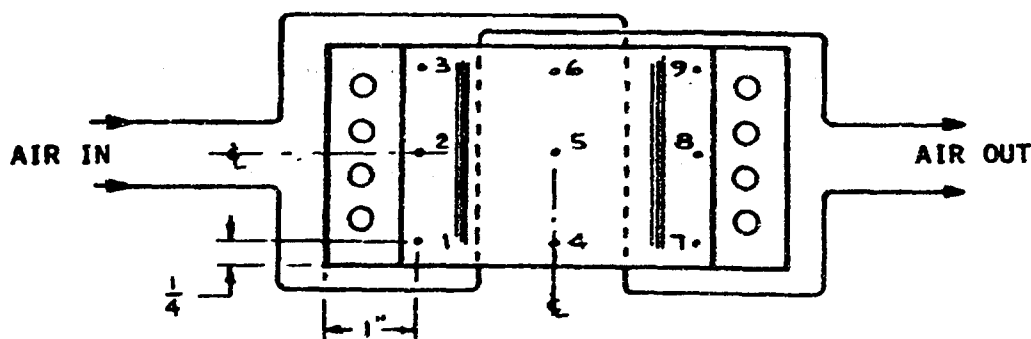


TABLE 4 - STACK C-2

Plate	1	2	3	4	Points 5	6	7	8	9
Plate Temperature °C									
Top									
1	95	98	95	98	102	99	92	94	93
2	93	102	94	102	112	100	93	99	93
3	100	103	93	119	127	103	96	105	92
4	102	105	92	124	139	110	109	107	100
5	100	104	92	131	148	112	112	113	98
6	102	110	91	133	149	115	112	118	98
7	104	110	93	137	155	121	110	110	100
8	103	110	102	126	139	125	105	113	103
9	103	110	102	133	152	130	104	113	103
10	110	115	95	141	148	110	106	107	97
11	114	118	95	138	148	115	107	108	97
12	112	118	97	138	145	117	104	112	98
13	98	110	104	-	-	-	98	105	98
14	98	110	104	123	129	117	102	108	99
15	114	110	103	117	123	117	99	102	99

TABLE 5 - STACK C-3

Plate	1	2	3	4	5	6	7	8	9
Plate Temperature °C									
Top									
1	97	103	107	102	110	112	103	106	110
2	99	107	110	103	112	115	101	109	112
3	102	110	113	101	111	113	103	108	110
4	101	109	112	107	115	119	101	113	117
5	100	108	114	106	116	119	106	116	117
6					116			113	115
7					117			115	120
8					115			112	118
9					115			111	117
10**	105	111	113	104	114	118	106	115	120
11					120				
12					124				
13					122				
14					119				
15	110	118	120	120	130	127	117	126	122
16					132			127	122
18					128			124	120
19					132			129	122
20**	107	114	118	114	124	114	110	122	118
21					130				
22					133				

\*\* 1/4" Copper bipolar plates

#### 4.1.4.1 Cont.

and the cooling air was admitted on one side of the hydrogen manifold.\*

#### 4.1.4.2 Electrodes and Catalyst Loadings

No work was performed under the subject contract to improve electrode performance and minimize precious metal catalyst loadings. (Catalyst loading is discussed in reports issued under Contract DAAK02-71-C-0297 and DAAK02-67-C-0219 (5,8).)

\*With a resultant increase in heat loss.

## 4.2 Thermal Cracker

### 4.2.1 Thermal Cracker - Description of Operation

The thermal cracker subsystem serves to convert liquid hydrocarbon fuels to a hydrogen rich gas stream. The subsystem includes all components and controls for continuous operation.

#### 4.2.1.1 Process

Military, logistic hydrocarbon fuels are thermally cracked into their constituent hydrogen and carbon in a high temperature, catalytic reactor. The hydrogen is given off as a gas and is passed to the fuel cell after suitable purification. The carbon is retained, in solid form, within the reactor bed. A regenerative system is used to provide the thermal energy required for cracking and to eliminate build up of carbon. At the end of the cracking cycle, the catalyst bed is returned to cracking temperature by combusting the product carbon within the reactor with air.\* Two parallel reactors are operated in sequence, to provide a continuous H<sub>2</sub> supply. A short purge follows carbon burn out to prevent oxygen, carbon monoxide, and carbon dioxide remaining in the reactor after burn off, from being passed to the fuel cell. During the purge cycle fuel is introduced into the reactor, as during the cracking cycle, but the product gas is vented.

The reactor timing sequence employed in the breadboard testing phase of this contract was based on results of a previous contract to investigate the thermal cracking process, Ref. 1, and preliminary investigation under this program. Total cycle length was 6 minutes. This was composed of 3 minutes cracking, 2-1/2 minutes burn off, and 1/2 minute purge.

The reactors were designed to operate at fuel flow rates from 0.8 to 2.5 lbs per hour.

#### 4.2.1.2 Control

A control system was constructed which measured the amount of fuel fed to the reactors during the purge and crack cycles and utilized this signal to control the amount of air admitted during the burn-off cycle. The reactors are equipped with automatic sequencing valves to direct products and reactants through the system. Details of this control system are

\*A complete mass and energy balance for this process is given in the appendix, Section A1.

#### 4.2.1.2 Cont.

presented in section 4.4 System Integration.

#### 4.2.1.3 Product Purification

The reactor product hydrogen contains two classes of impurities, impurities present in the hydrocarbon feed stock and impurities resulting from the regenerative cracking process. Typical feed stock impurities are sulfur and lead. Product gas impurities are carbon monoxide, carbon dioxide, methane and carbon dust.

Of the impurities listed above, carbon dioxide and methane are harmless to the fuel cell operation and therefore require no treatment. Techniques were developed under this program for the removal or control of the remaining listed impurities resulting in a product stream suitable as fuel for the phosphoric acid fuel cell.

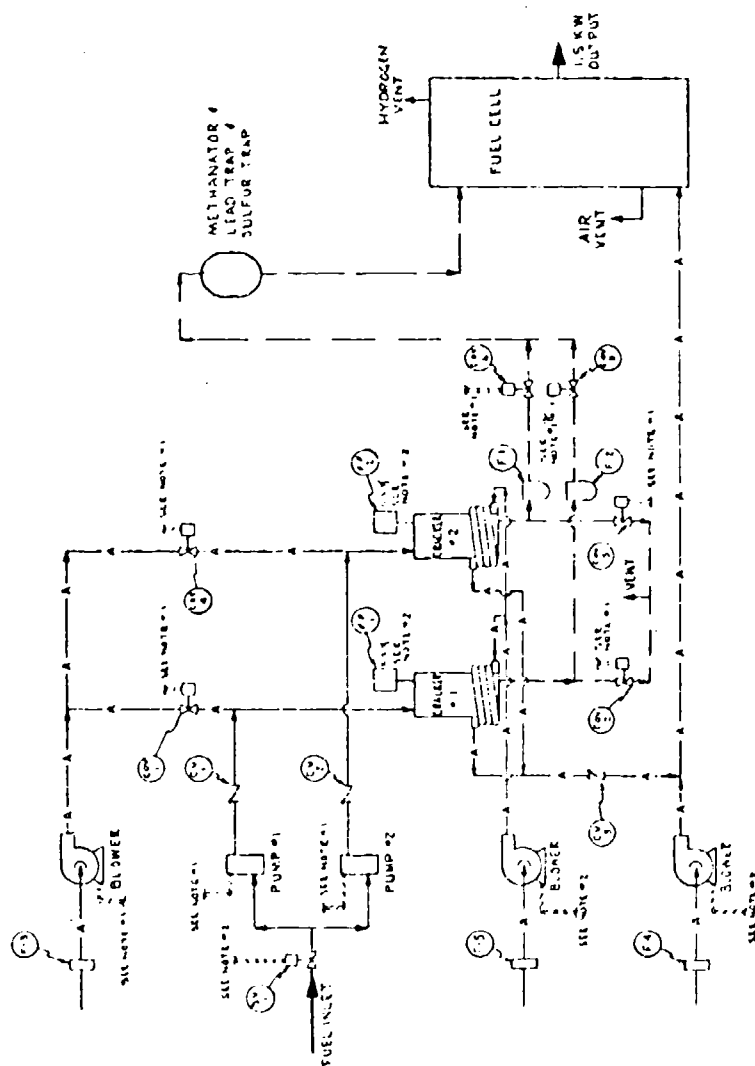
A flow schematic of the thermal cracker, fuel cell system is shown in Fig. 11.

SYMBOL	COV	DESCRIPTION	AMOUNT
		CAM OPERATED VALVE	6
		CV CHECK VALVE	3
		CV FILTER	3
		FF FLAME FAILURE	2
		SENSOR	1
		SV SOLENOID VALVE	1

LINE LEGEND

FUEL	---
PRODUCT GAS	---
AIR	---A---
ELECTRICAL	####

NOTES:  
1-REFER TO FUEL/AIR CONTROL  
SYSTEM BLOCK DIAGRAM  
B-1513 FOR INTERRELATIONSHIP  
OF CONTROLS.  
2-REFER TO ELECTRICAL BLOCK  
SCHEMATIC C-15B12 FOR  
INTERRELATIONSHIP OF CONTROLS.



FLOW SCHEMATIC  
FIG. 11

#### 4.2.2 Cracker Catalyst Evaluation

Several catalysts were investigated with the objective to determine the activity as defined by conversion of hydrocarbon fuel into gaseous products and the selectivity as defined by the hydrogen content in the gaseous products. The following types of catalyst were tested: Platinum on alumina, nickel on alumina, nickel on ceramics, metallic nickel and inconel.

Initial catalyst screening tests were conducted in a small inconel test reactor containing a catalyst charge of approximately 450 ml. The reactor was heated electrically to 800-900°C and operated at atmospheric pressure. Fuel ("BP" regular gasoline) was added so that the weight hourly space velocity (WHSV) varied between 0.2 and 1. The duration of fuel admission was 3 minutes- the duration of burn-off was 1.5 minutes resulting in a 4.5 minute cycle. The total gaseous product was measured and samples were analyzed by means of infrared spectrophotometry.

The data of these tests are given in Table 6. These results indicate no advantage is gained through the use of platinum catalysts in the thermal cracker. Solid metallic nickel in form of chips appears to be suitable for this operation. Conversion in these tests was low, apparently because of the particular bed configuration used for screening of catalysts.

Catalyst testing was also conducted in full size thermal crackers and the results of the screening tests were verified (see Thermal Cracker Testing Summary Tables 10 to 17, Appendix A-II). Metallic nickel was chosen as the cracking catalyst for the breadboard system.

#### 4.2.2 Cont.

TABLE 6

#### Evaluation of Catalysts for Thermal Cracker

<u>Catalyst</u>	<u>WHSV</u>	<u>Percent Conversion</u>	<u>Product Analysis</u>		
			<u>CO</u>	<u>CH<sub>4</sub></u>	<u>H<sub>2</sub>**</u>
0.5% Pt 1/8"Al <sub>2</sub> O <sub>3</sub> Pellets	0.41	27	18	.2	81.8
0.5% Pt 1/8"Al <sub>2</sub> O <sub>3</sub> Spheres	0.45	22	-	24	76.0
0.5% Pt on Al <sub>2</sub> O <sub>3</sub> Spheres	0.40	48	6.0	5.5	88.5
C-5483	0.62	20			
	0.95	59			
0.5% Pt on Al <sub>2</sub> O <sub>3</sub> Spheres	0.45	40	-	1.3	98.7
(same after use for 37hrs)	0.67	31			
	1.03	50			
20% Ni on Al <sub>2</sub> O <sub>3</sub>	0.41	0	7.5***	34	58.5
C-5582	0.62	0			
	0.95	41			
	1.45	44			
20% Ni on Al <sub>2</sub> O <sub>3</sub>	0.39	18			
C-5581					
Raschig rings coated	0.28	2	2.8	14.2	83
with Ni	0.47	35			
Ni chips 3/8"x3/4"x1/16"	0.35	30	-	8	92
Bent to form tube	0.23	33	-	10.5	89.5
	0.19	15			
	0.44	50			
	0.66	58	.3	13	86.7
Nickel chips	0.19	15			
(same after use for 30	0.23	37			
hrs)	0.66	57			
Mixture of Inconel	0.23	0	2.9	32.9	55.1
and Norton Rings	0.36	21			

\*Conversion based on theory for 100% conversion to H<sub>2</sub> and using C<sub>8</sub> fuel.

\*\* H<sub>2</sub> by difference

\*\*\*CO<sub>2</sub>

#### 4.2.2 Cont.

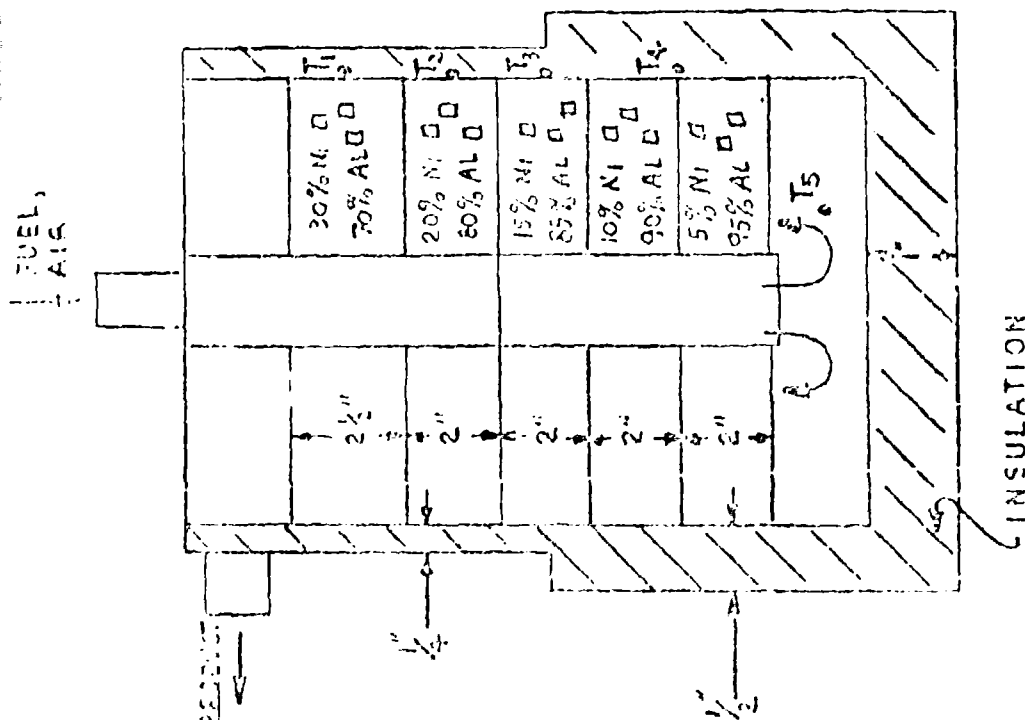
Testing conducted in full size reactors revealed two problem areas with metallic nickel catalysts:

A. It was observed that when nickel or Inconel are used as catalyst with no dilution with inerts, plugging of the catalyst bed occurs. Fuel contacting the pure nickel is almost entirely cracked to carbon in a relatively short section of the catalyst bed. During subsequent burn-off a high temperature zone develops where the most carbon was deposited and can cause the nickel to melt and agglomerate.

B. The nickel oxidizes during the burn-off cycle. The oxidation rate increases rapidly with an increase in catalyst operating temperature. The nickel oxide reacts with the hydrogen produced during the fuel cycle and produces undesirable water and carbon monoxide. Because carbon monoxide is an inhibitor for the fuel cell catalyst, the product gas stream must be methanated to remove CO by converting it to  $\text{CH}_4$ . For every mole of CO reacted, three moles of hydrogen are reacted and are lost. In addition, it was found that the catalyst needed a certain "initiation time" before reaching a satisfactory activity. The initiation period was 20 to 30 hours. The reasons for this are that with time, due to nickel migration, a layer of nickel is deposited on the alumina diluent. Observation of used alumina Raschigs proved the nickel migration theory.

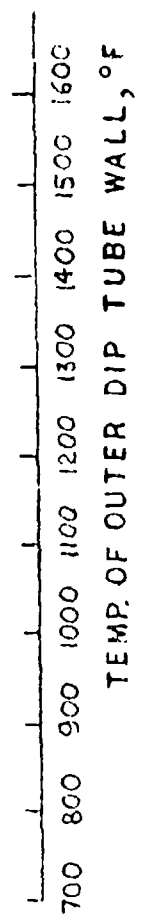
In order to eliminate plugging as described in A above, further experimentation was performed using as catalyst 1/4" nickel Raschig rings diluted with 5/16" OD x 5/16" Lg x 1/8" Dia Bore, SA-103 Norton Alumina Raschig Rings. Additionally, in order to deposit the carbon uniformly over the entire length of the catalyst bed, and in this manner avoid hot spots during the burn-off cycle, the concentration of nickel is the lowest at the inlet of the catalyst bed and increases gradually towards the outlet of the catalyst bed. The best results were obtained when the catalyst bed consisted of 5 evenly spaced layers starting at the inlet: The 1st layer of 5% Ni, the 2nd of 10% Ni, the 3rd of 15% Ni, the 4th of 20% Ni, and the 5th of 30% Ni. Fig. 12.





RUN # 38  
 BASIS:  
 FUEL JP-4 -  $2\frac{1}{2}$  lb/hr  
 AIR - 350 SCFH  
 O/C = 1.76

CYCLE TIME:  
 FUEL -  $3\frac{1}{3}$  MIN.  
 AIR -  $2\frac{1}{3}$  MIN.  
 WAIT -  $\frac{1}{3}$  MIN.



LEGEND    □    START OF AIR CYCLE  
              ○    END OF AIR CYCLE

REACTOR B - 15705 NO. 8  
 CATALYST B - 15707 NO. 11

TEMPERATURE PROFILE THROUGH REACTOR

#### 4.2.2 Cont.

The nickel catalyst proved to be an excessent catalyst for cracking hydrocarbon fuels to hydrogen and carbon. Diluted with alumina in a manner described above, it performed without plugging and without hot spots. No decrease in catalyst activity was observed after 80 hours of operation.

#### 4.2.3 Cracker Material of Construction

Inconel 600 was used as construction material in the manufacture of all crackers. Inconel 600 proved to be a satisfactory material for cracker construction. However, even more superior performance is claimed by the manufacturer for Inconel 601.

In order to further evaluate materials of construction three rods of Inconel 600, Inconel 601 and Incoloy 800 were tack-welded along the entire lengths of the cracking chambers of initial reactors. After reactor disassembly, the rods showed no damage or difference in physical appearance by visual inspection.

Due to the number of crackers tested in this investigation, it was not possible to perform a life test on any single design. The longest operating times were approximately 80 hrs on reactor No. 8, and 80 hours on reactor No. 9. After these 80 hours of operation no visible mechanical defects could be detected on either of these two reactors.

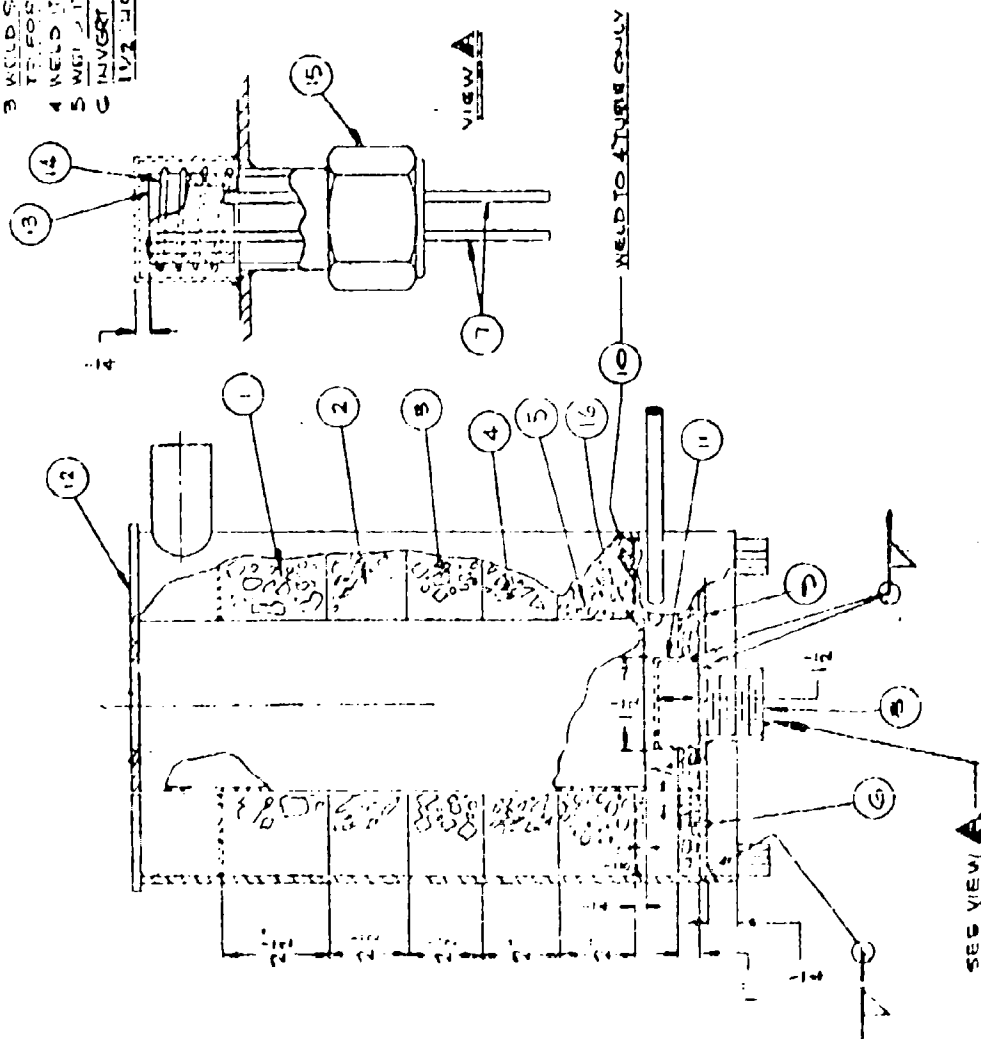
#### 4.2.4 Thermal Cracker Vessel Design

Testing was performed on three basic reactor configurations, straight tube, dip-tube with catalyst in the dip-tube and dip-tube with catalyst in the annulus.

The dip-tube configuration with catalyst in the annulus provided the most uniform temperature distribution over the bed (see Fig. 12), providing effective catalyst utilization and resistance to carbon plugging (see Sect. 4.2.5) and "hot-spotting." A design with fuel and air flow downward through the dip-tube and upward through the annulus was employed in the breadboard system. This flow path allowed a simplified physical layout of the breadboard system. The breadboard reactor is detailed in Fig. 13 and 14.

# ORDER OF ASSEMBLY

- 1 INVERT ITEM 12
- 2 ELONGATE USE OF REACTOR WITH  
CAPACITY ITEMS 1, 2, 3, 4 & 5
- 3 WELD SCREEN ITEM 10 TO TUBES  
TO FORM THE ANNULUS SEE NOTE
- 4 WELD ITEMS 5 & 6 TO ITEM 2
- 5 WELD ITEM 7 TO ITEM 12
- 6 INVERT ITEM 12 & ADD ITEMS 6 THRU  
1/2 HOLE ON TOP

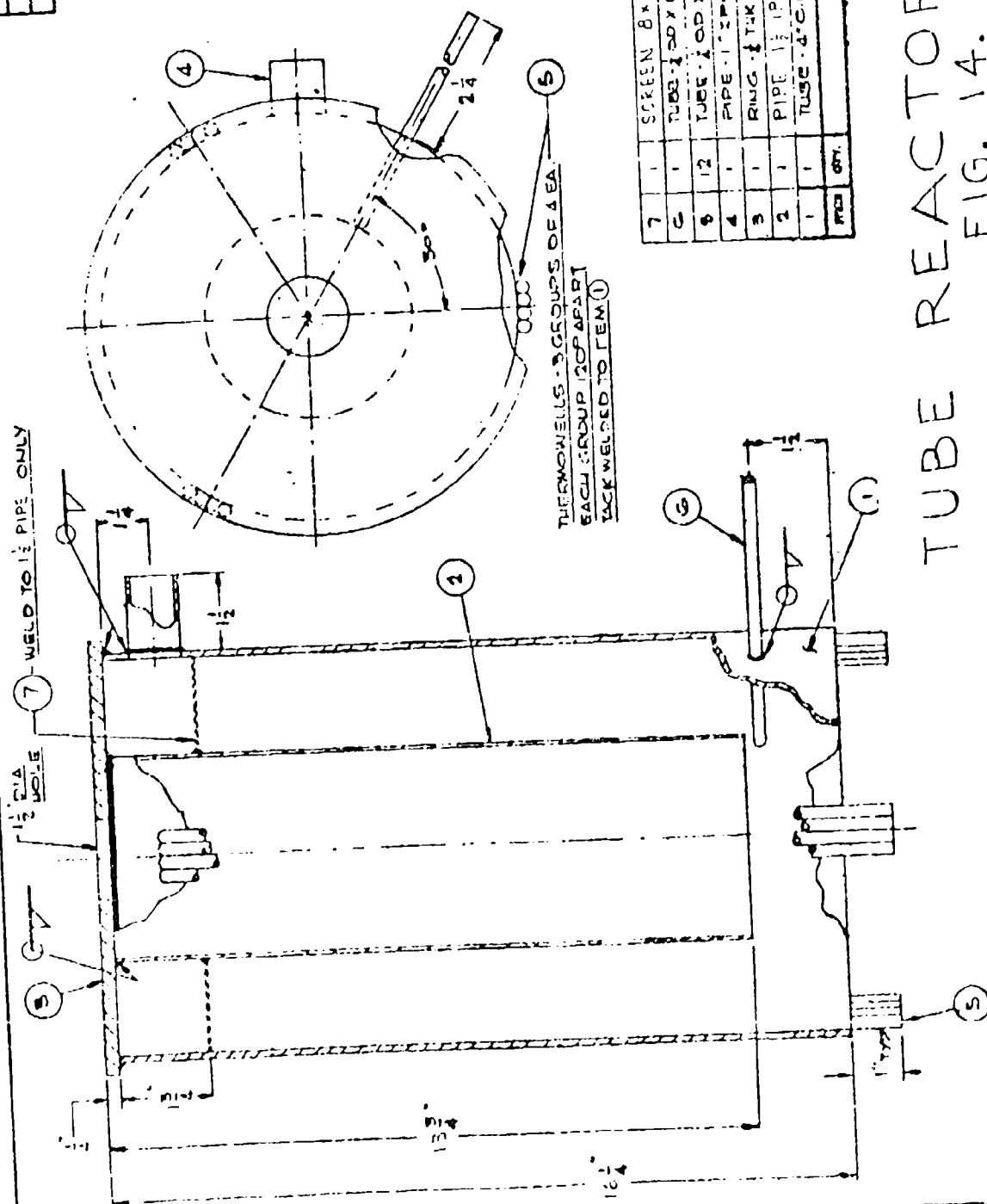


ITEM	QTY.	DESCRIPTION	UNIT
16	1	SUPPORT PINS	INCOSEL 600
15	1	FITTING 3/4" NPT	CONAX
14	1	WIDE-PLATE 0.22 DIA X 10" LONG	
13	1	TUBE ALUMINA 7/8" OD X 1/2" WALL X 1' LONG	
12	1	SIP TUBE REACTOR # 11	B-15790
11	1	SCREEN CUP 8X8 MESH OCS WIRE	INCOSEL 600
10	1	SCREEN 8X8 MESH OCS WIRE	INCOSEL 600
9	1	RING 1/4" THK	INCOSEL 600
8	1	COUPLING 3/4" FULL	316 S.S.
7	2	ROD 7/8" DIA 6" LG	INCOSEL 600
6		WORTON ALUMINA RASCHIGS 5/16"	
5		5/16" BY VOL 1/4" NICKEL RASCHIGS	
4		5/16" BY VOL 5/16" ALUMINA RASCHIGS	
3		10% BY VOL 1/4" NICKEL RASCHIGS	
2		25% BY VOL 5/16" ALUMINA RASCHIGS	
1		20% BY VOL 1/4" NICKEL RASCHIGS	
1		30% BY VOL 1/4" NICKEL RASCHIGS	
1		70% BY VOL 5/16" ALUMINA RASCHIGS	

## LIST OF MATERIAL

REACTOR INTERNAL  
FIG. 13.

WELDON TO 1/2 PIPE ONLY



7	1	SCREEN 8 X 8 MESH - .065 DIA WIRE (CUT)	INCONEL 600
8	1	PIPE 1.00 X .035 WALL X 5' 0" <sup>2000 PSI</sup> <sub>1000 PSI</sub>	
9	12	PIPE 1.00 X .018 WALL X 14' 0" <sup>2000 PSI</sup> <sub>1000 PSI</sub>	
10	1	PIPE 1.125 X 4' 0"	
11	1	RING 1/2" THK	
12	1	PIPE 1 1/2" IPS SCH 40	INCONEL 600
13	1	PIPE 3" O.D. X 1/2" THK	INCONEL 600
DESCRIPTION			QUANTITY
14	871		

TUBE REACTOR EXTERNAL  
FIG. 14.

#### 4.2.5 Carbon Management

In an ideal thermal cracker, carbon should be deposited uniformly within the catalyst bed during the cracking cycle. Uniform carbon deposition allows maximum catalyst utilization, prevents localized build-up resulting in carbon plugging and prevents reactor damage due to "hot spotting" as described in Sect. 4.2.2. A second consideration is that the carbon should be of a form that will adhere to the catalyst bed and not be lost as dust during the cracking or burn-off cycles. Dusting may result in loss of process efficiency and may cause valve leakage or fuel cell damage if any carryover is allowed.

##### 4.2.5.1 Carbon Build-Up

Initial testing with straight tube and early dip-tube reactors produced frequent cases of carbon build-up significant enough to cause reactor plugging. To investigate this phenomenon two testing procedures were used.

A. A straight tube reactor was deliberately plugged by subjecting it to an extended cracking cycle. The reactor was then cut apart for inspection to determine location and nature of the plugging.

Carbon deposition and plugging started to occur approximately 1/2" from the start of the nickel catalyst and continued for another 4 or 5 inches. A substantial amount of nickel and inconel Raschigs were melted and agglomerated together with carbon into one mass. This caused the entire catalyst bed to settle approximately 2-1/4".

B. All subsequent reactor tests were fitted with manometers to allow observation of pressure drop across the catalyst bed. An increase in pressure drop in the course of several burn-off cycles was a direct indication that cumulative plugging conditions were present.

These tests showed that plugging was principally a

#### 4.2.5.1 Cont.

function of both oxygen-carbon ratio and catalyst activity. In all reactors in which reasonably homogeneous temperature gradients were maintained, and in which alumina diluted catalysts were employed, no tendency to plug was observed at oxygen to carbon ratios of greater than 1.6. In reactors operating with high activity catalysts plugging, occurred in the first few inches of the catalyst bed indicating that the cracking reaction was occurring only in this region. As a result, subsequent reactors were constructed with catalyst beds employing an alumina diluent. Extreme temperature gradients across the catalyst bed similarly caused plugging by producing areas of high activity (hot zones). Acceptable temperature gradients were achieved by redesign of the dip-tube reactor to incorporate the catalyst in the annulus, rather than in the dip-tube. Due to higher heat losses and shorter heat transfer path of the catalyst bed, the dip-tube reactor with the catalyst in the annulus, will perform at lower, more uniform temperatures.

The dip-tube reactors of this type operated successfully in the breadboard system at fuel rates from 0.8 lbs/hr to 2.5 lbs/hr and at an oxygen to carbon ratio of 1.6 without plugging.

#### 4.2.5.2 Carbon Dusting

Initial thermal cracker testing revealed that approximately 3-4% of the carbon formed was being lost in the form of a fine dust carried out in the hydrogen product stream. While this amount would not significantly affect the mass and energy balance it is detrimental to operation of the hydrogen control and purification ancillaries and the fuel cell. Because of the quantity of carbon involved a carbon filter would not be acceptable for extended missions. As a result, techniques to eliminate carbon release from the reactor were investigated.

An internal carbon filter was abandoned when in the course of testing it was discovered that carbon dusting did not occur at cracker operating temperatures below 1600°F. As a result, the use of the dip-tube reactor with catalyst in the



4.2.5.1 Cont.

annulus permits operation at peak temperatures below 1600°F and carbon dusting is eliminated.

Because of the possibility of some carbon carryover in the event of a malfunction, a small carbon filter was incorporated into the design of the advanced development model power plant.

#### 4.2.6 Thermal Cracker Start-Up

The purchase description calls for a system start-up time of 15 minutes in a -25°F ambient. Ideally the cracker should be capable of a more rapid start-up as a portion of the heat produced may be used for fuel cell heating (see Section 4.4.2).

For cracker start-up, fuel and air are simultaneously introduced into the cracking chambers through the normal flow paths. Combustion is initiated by a Pt/Rh ignitor (see Section 4.2.7). Fuel flow is controlled to 2.5 lbs/hr to each reactor by the Fuel Pump Rate Controllers set to the purge rate (see Section 4.4.1.3). The cracker air blower is operated on the high speed winding delivering approximately 800 scfh to each reactor. A temperature over-ride shuts off blower and pumps when operating temperature is attained.

Use of this start-up system in conjunction with the ignitor described in Section 4.2.7, resulted in typical cracker start-up times of approximately 12 minutes for the breadboard system. Start-up times as low as 8 minutes were recorded.

#### 4.2.7 Ignitor

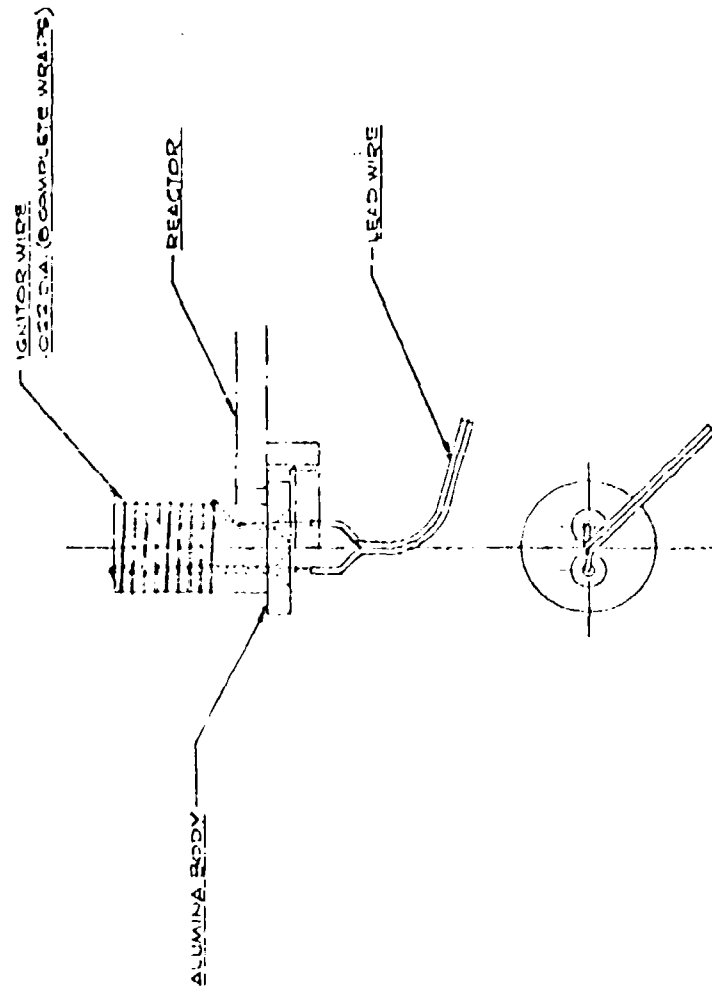
The function of the ignitor is to initiate combustion of the air and fuel during start-up. Initially an external burner was tested but abandoned in favor of an ignitor installed within the cracker vessel with combustion occurring within the cracking chamber.

Preliminary testing was conducted with a commercially available gasoline burner (Hauck Co. Model WHD-11) both in standard and modified form. This unit was unsatisfactory for cracker start-up for the following reasons: The burner flame was not stable against cracker back pressure, the burner would not start without pre-vaporization of fuel and the burner size and weight were excessive.

An electrically heated catalyst bed within the reactor vessel was then designed and tested. Ignition was achieved by this method but start-up times were excessive.

In the course of this testing it was discovered that ignition was not occurring on the catalyst bed but on the platinum/rhodium heating element itself. As a result the ignitor incorporated in the breadboard system and specified for the ADM consists of a platinum/rhodium wire coiled on a ceramic tube and equipped with suitable electrical leads. The ignitors in the breadboard reactors were mounted on the bottom of the reactor directly at the dip-tube exit. In operation ignition started on the heated ignitor coil. Once combustion was achieved the flame zone was stable and the ignitor could be turned off.

Testing of the breadboard system resulted in cracker start-up times in the range of 11-15 minutes using combat gasoline and JP-4. Power to the ignitor coil was 156 watts for one minute. The ignitor is shown in Fig. 15.



IGNITOR ASSEMBLY  
FIG. 15

#### 4.2.8 Valve Design

For the selected ADM design, each thermal cracker requires three valves for air in, air out, and product out. The requirements for each of these valves vary considerably and are summarized below. No inlet fuel valve was required due to the nature of the fuel injection system employed.

<u>Valve</u>	<u>Requirements</u>
Air In	Low pressure drop at high air flow (start-up 800-1000 scfh)  Ambient temperature.
Air Out	Low pressure drop at high air flow.  900°F operation.
Product Out	Pressure drop not critical.  Flow approx. 80 scfh 700°F operation preferred, however lower temperature operation can be provided by cooling the cracker product stream.

In addition to these specific requirements, all valves should be light weight, have low leakage, require low power for actuation and meet the requirements of the purchase description.

Initially a vendor survey was conducted to determine the suitability of commercially available valves. No valves were found that were suitable for the high temperature, air out stream without imposing severe pressure drop or weight penalties. As a result, the design of special valves was initiated.

Development included both the valves and the valve actuator mechanism. The operator chosen was a cam rack driven by an electric motor. This method has the advantage of requiring a single, low power motor for actuation. A valve configuration similar to automobile combustion chamber valves was chosen. This configuration has proven to be capable of operating at high temperatures and is easily integrated with a cam type operator. The valve used for breadboard testing

#### 4.2.8 Cont.

(Fig. 16) has the following characteristics:

Configuration	Push to open, plug and seat valve with spring closure.
Construction	Fabricated all welded construction.
Material of construction	316 Stainless Steel
Leakage	Approx. 0.025 scfh at 2.5 psig and 1000°F.
Pressure drop	1.7" H <sub>2</sub> O at ambient temperature and 325 scfh air.

The valve design specified for the advanced development model design employs a cast body due to difficulties encountered with warpage during welding of the breadboard reactor valves.

Product out valves in all breadboard testing were manufactured by Clippard Instrument Control. As the maximum operating temperature of these valves is 400°F, a hydrogen cooler consisting of a 12 inch length of 3/8 in. O.D. stainless steel tubing was installed between the thermal crackers and product out valves. This arrangement gave satisfactory service in all breadboard testing and has been retained in the ADM design.

#### 4.2.9 Valve Testing

Prior to installation on the breadboard thermal crackers, the air-in and air-out valves were leak-tested at both ambient and high temperature.

Three models of the same basic configuration were constructed. The purpose of the first model was to test adequacy of packing, to test operation at high temperature, to determine seat leakage, and to check integration of the valve and cam operator. A source of nitrogen at 2.5-3.0 psig (approximate cracker operating pressure) was connected to the valve. The valve was operated by the cam for a total of 24 hours at a rate of 1 cycle/minute. At the end of this time, leakage across the seat was measured at 0.021 scfh. Leakage through the packing was checked by applying a leak detecting fluid. No bubbles were visible. The method of testing is illustrated in Fig. 16. Only light finger tightening of the packing nut was necessary. The packing consisted of a modified Conax Corp., Model PG-2 packing gland. The modification utilized two teflon packing rings instead of one as is standard (refer to Fig. 18).

The second phase of testing on this valve was operation at high temperature. Air at a flowrate of 200 scfh was heated to 1000°F. This was done by adding hydrogen to air and then catalytically combining the hydrogen and oxygen in an Engelhard Model "D" Deoxo purifier containing a precious metal catalyst. The reaction is exothermic thus, in an insulated vessel, the outlet air temperature is proportional to the hydrogen added. Approximately 6% by volume hydrogen is required to achieve a temperature of 1000°F. The valve was operated for 6 hours at 1 cycle/minute. During this time the valve operated satisfactorily and the packing area was only warm to the touch. Seat leakage was not measured quantitatively during this test. During that portion of the cycle in which the valve was closed, the tubing connected to the valve outlet was placed in a beaker of water. The rate at which bubbles escaped did not appear to exceed the rate measured at ambient temperature as previously described. The method of testing is illustrated on Fig. 17.

The second model was constructed of thin wall tube

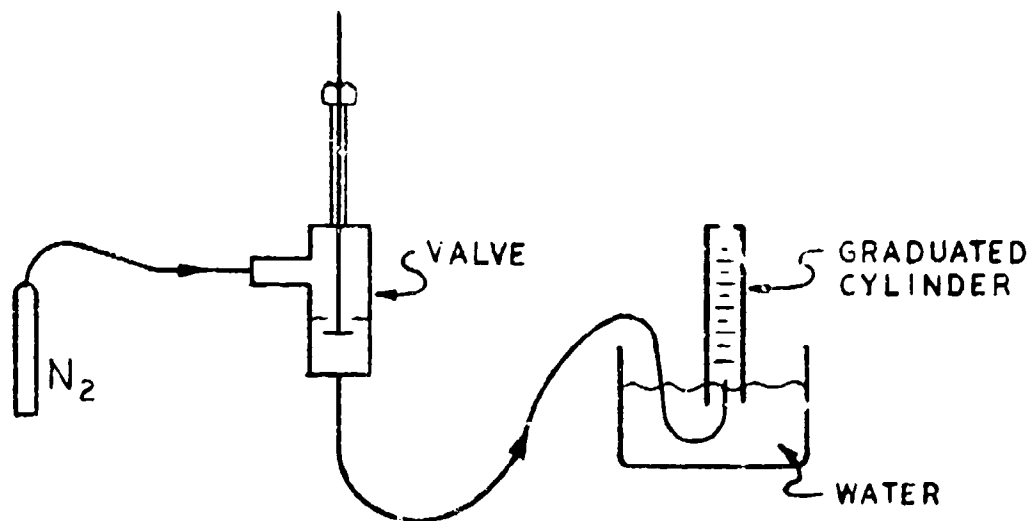


FIG. 16 VALVE LEAK TEST

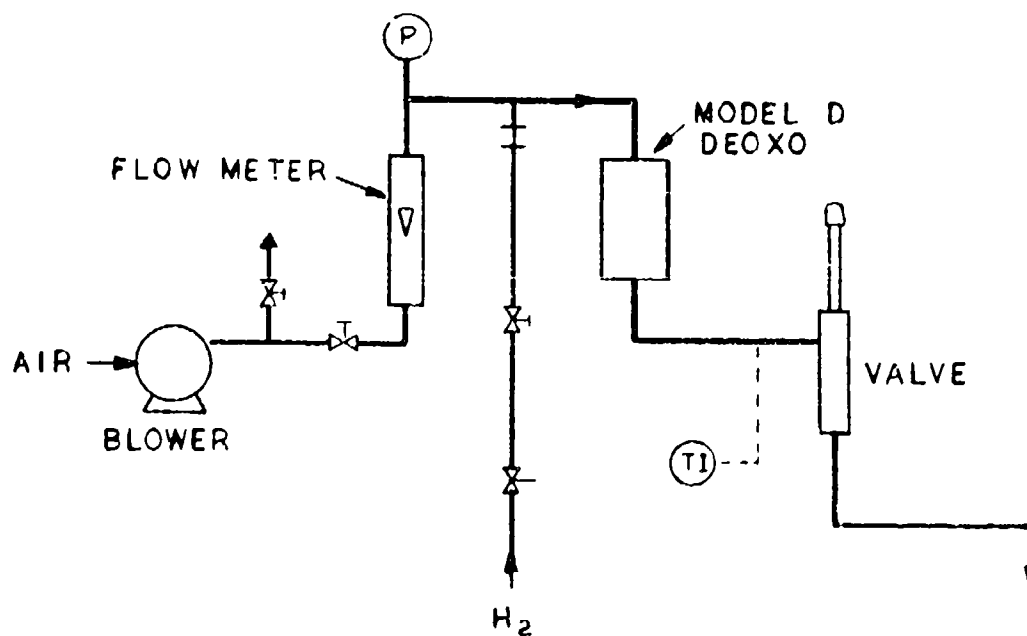


FIG. 17 HIGH TEMPERATURE VALVE TEST



#### 4.2.9 Cont.

in order to minimize weight. The leak rates across the seats were excessive due to warpage from welding. The warpage was particularly evident in the bonnet. The packing, which is part of the bonnet provides alignment of the stem in the valve. Thus, it is evident that warpage will affect the leak rate across the seat.

Based on this experience an improved and final model (Fig. 18) was designed that was incorporated on the breadboard. Improvements over previous models are listed below:

- A. Body wall thickness was increased to 0.120".
- B. Two welds were eliminated in the body to bonnet connection by machining the bonnet and cover from one piece.
- C. Bonnet wall thickness was increased to 0.052".
- D. Valves were stress relieved after welding.
- E. Valve seats were honed.
- F. A stem centering guide was added to compensate for warpage (see detail E, Fig. 18).
- G. A stem twisting mechanism was added to aid in seating the plug.
- H. Aeroquip Corp. J13 gasketless joints were installed to provide a quick removal capability from the crackers for inspection and servicing if necessary.

Improvements A - D were incorporated to reduce warpage due to welding.

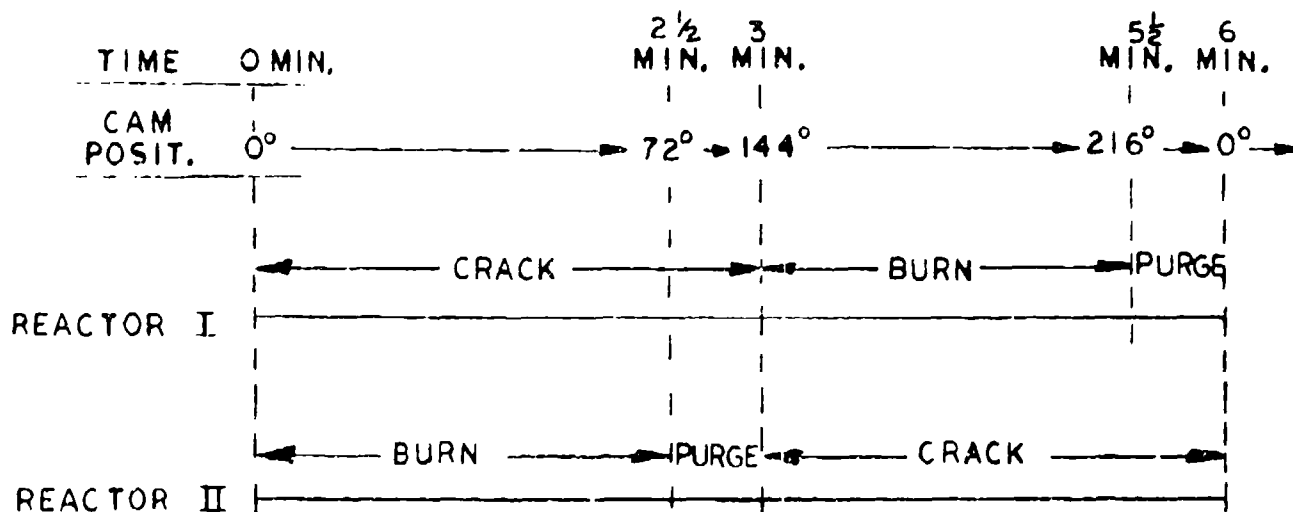
These valves proved satisfactory in over seventy hours of breadboard system operation. Difficulties, however, were encountered in maintaining alignment between the cam followers and the valve stems. This problem area has been eliminated in the ADM design by making the four valves in a single casting and mounting the cam operator directly on this casting.



#### 4.2.10 Valve Drive

Sequencing and actuation of the cracker valves on the breadboard system was accomplished by means of a motor driven cam rack controlled by a cam timer. The timing sequence and valve configurations used are shown in drawing Fig. 19. The cam timer consists of four cams rotating at 1/6 RPM. Each cam activates a microswitch with each switch corresponding to one of the four running cam positions shown in Fig. 19 (0°, 72°, 144°, 216°). When the timer calls for a new valve configuration, the valve drive cam rack is indexed to the proper position. The time required to index between two positions is approximately one quarter of a second. Dynamic braking was employed to prevent over-run. Slow lift rapid closure cam profiles were employed to actuate the air valves. This configuration reduces the valve drive power requirement and helps ensure positive valve seating.

In addition to actuating the cracker valves the cam rack also actuated the sequencing switches for the fuel-air control system. On the breadboard system the cams were cut only for the four "run" valve configurations. The start-up valve configuration being obtained by manual over-ride.



## VALVE CONFIGURATIONS

		REACTOR I				REACTOR II			
VALVE		FUEL PUMP	FUEL OUT	AIR IN	AIR OUT	FUEL PUMP	FUEL OUT	AIR IN	AIR OUT
CAM POSIT.	0°	ON	O	C	C	OFF	C	O	O
	72°	ON	O	C	C	ON	C	C	O
	144°	OFF	C	O	O	ON	O	C	C
	216°	ON	C	C	O	ON	O	C	C

START-UP	268°	ON	C	O	O	ON	C	O	O
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O — OPEN  
C — CLOSED

## THERMAL CRACKER CYCLE

FIG. 19

#### 4.2.11 Treatment of Cracker Product Gas For Removal of Lead and Sulfur

Combat gasoline contains 0.05 to 0.1 wt. % of sulfur and 2.11 to 3.17 g of lead per gallon. In addition the content of scavengers for lead may be up to 1% Cl as ethylene dichloride, 0.5% bromine as ethylbromide, and 0.3% P as tri-cresylphosphate to yield a total quantity theoretically adequate for lead scavenging.

JP-4 fuel, according to Mil Spec T5624G, may contain a maximum of 0.4 wt. % of sulfur whereas mercaptan sulfur is allowed to be 0.01% maximum.

The combat gasoline used in our experimental work contained 769.1 ppm S and 717.2 ppm Pb; the UP-4 employed contained 8.2 ppm Pb and 62.1 ppm S.

No appreciable quantities of Pb or S can be allowed to be present in the product gas fed to the fuel cell anode to avoid inhibition of the anode catalyst. Product gas from the cracker exhibited only a low sulfur content, (apparently in the form of  $H_2S$ ), under the condition of operation. In one case the S-level between the thermal cracker and the methanator was 22 ppm and 0 ppm after the methanator; in a second test, the gas contained 90 ppm of S upstream and about 50 ppm downstream of the methanator. In the latter case the cracker had been operated on combat gasoline with a fuel flow of 1.5 lbs/hr. The reactor skin temperature was 1550°F and the methanator temperature was 780°F. The methanator contained 1.63 lbs of Girdler catalyst G65RS which contains 25% of Ni. The residual 50 ppm  $H_2S$  had no adverse effect on the anode catalyst during this testing. It appears that an additional ZnO filter should be employed to protect the fuel cell. Assuming a maximum of 100 ppm of sulfur in the gas as an upper level, in 1000 hours about 150 g of sulfur would have to be retained, which could be achieved with a cartridge containing one pound of ZnO. This filter should be installed as a replaceable cartridge upstream from the methanator.

Regarding the influence of lead in combat gasoline, no adverse effects have been observed in our runs. Tetraethyl lead is thermally unstable. Its decomposition in admixture with hydrocarbon fuels has been repeatedly studied, and the

#### 4.2.11 Cont.

use of a thermal treatment for removal of lead from gasoline has even been patented (U.S. 2,470,634). Upon rapid heating of gasoline to temperatures of 750-850°F, lead was essentially removed in the form of metallic lead, lead sulfide and lead bromide (the percentages in this particular case being 23.7, 71 and 2.4 per cent respectively). Hence, under the conditions of thermal cracking, no gaseous form of lead is expected in the product gas. Only lead in particulate form would leave the cracker, but would be retained by the sulfur filter or by the methanator.

In the use of combat gasoline at a rate of about 2.2 lbs per hour as required for the operation of the 1.75 kw system, about 1 g of lead per hour as metal or in the form of compounds will be thermally generated in a zone of the cracker at which the temperatures are still below cracking temperatures. As stated above, in our runs no adverse effect of lead has been observed. The formation of lead bearing deposits may, however, cause problems over the long periods of time by causing an increase in pressure drop or by interfering with the action of the cracking catalyst. This subject requires further study, which should be carried out in Phase II of this program. Several alternates should be considered, e.g. designing a thermal decomposition zone which can be periodically cleaned, or development of lead removal filter cartridges from the gasoline such as described in U. S. patents 2,368,201; 2,369,124; 2,390,988; 2,392,846; 2,745,793.

#### FOOTNOTE:

##### H<sub>2</sub>S Analysis

In the thermal cracking of hydrocarbon fuels, the principal product of the thermal cracking operation is hydrogen. Therefore, the major sulfur compound present in the gaseous product will be hydrogen sulfide. Using the method described in "Gas Analysis" by Altieri, p. 347, the H<sub>2</sub>S concentration in the gaseous product obtained in our screening program for catalyst was found to be approximately 25 ppm. This H<sub>2</sub>S level found in our laboratory tests resulted from use of regular gasoline.

In order to ascertain that all sulfur in the gaseous

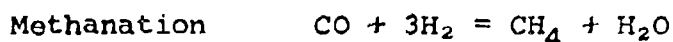
FOOTNOTE: Cont.

product was determined, a procedure was developed to analyze the product gas for total sulfur content. The analysis was performed by mixing the product gas with approximately 75-80% air. This mixture was then passed over platinum gauze at a temperature of 700°C. The oxidized sulfur was then scrubbed out with dilute hydrogen peroxide solution. This solution was then acidimetrically titrated to determine per cent sulfur. The level of detection for this analysis is felt to be 2-3 ppm S.

Samples from actual thermal cracker runs were analyzed by this method. The results have been stated in the preceding section. Essentially, the sulfur is present as H<sub>2</sub>S.

#### 4.2.12 Carbon Monoxide Control

Excessive concentrations of carbon monoxide, greater than 1%, in the hydrogen stream will impair fuel cell efficiency through inhibition of the anode catalyst. Two common methods of carbon monoxide control are available, shift conversion and selective methanation. These reactions are shown below.



On the surface it appears that shift conversion is the ideal carbon monoxide removal process due to the hydrogen gained. Shift conversion, however, was not investigated in this program due to four significant drawbacks.

1. The cracker product stream contains inadequate water for the reaction. An "on board" water addition system was ruled out due to constraints of low temperature operation.
2. Available shift convertor catalysts are highly sulfur sensitive.
3. The shift reaction is temperature critical requiring close temperature control.
4. Large volumes of catalyst are required for the shift reaction.

As a result methanation was the chosen method of CO removal.

A methanator was tested to determine the efficiency and consequently the quantity of catalyst required. The methanator was charged with 1.6 pounds of nickel catalyst cylinders, 3/16" nominal size. This is a pre-reduced and stabilized nickel oxide catalyst with a recommended operating temperature range of 400-900°F.

An electric heating element was placed around the above mentioned methanator and the vessel was insulated with a one inch thickness of Babcock & Wilcox Company, Kaowool



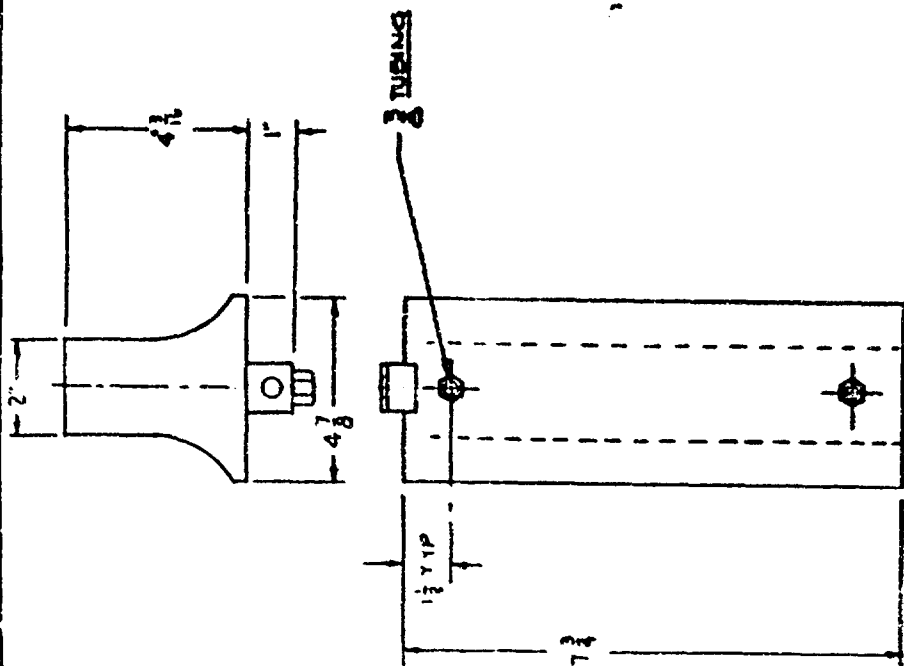
#### 4.2.12 Cont.

blanket. The heating element was connected in series with a variable resistor so that the power to the heater and consequently the operating temperature of the methanator could be varied. Analysis of the methanator exit gas by both infrared and chromatograph revealed no carbon monoxide at inlet concentrations up to 12.0%. The data are tabulated in Table No. 87.

These results led to the design of a smaller methanator combined with the lead and sulfur trap. (Refer to Fig.20) The methanator portion of the combination vessel contributes about 1.5 pounds to the system weight.

The combined lead and sulfur trap and methanator is positioned between the two thermal crackers, utilizing space that would not otherwise be used. No electric heaters are necessary as the close proximity to the reactors, and the "fin" shape provides excellent heat transfer by radiation. Operating temperature is not critical as borne out by excellent performance over the range of 420-900°F of the methanator described in Table 7. Radiation heat transfer experiments predicted an overall heat transfer coefficient to be 6 Btu/hr/ft<sup>2</sup>/°F. The heat-up time for the unit is calculated to be 12 minutes.

DATE	REVISION	BY	CHK



METHANATOR, SULFUR & LEAD TRAP ASSEMBLY  
FIG. 20.

TABLE No. 7

Summary of Methanator Performance

(Space Velocity 2000 Hrs<sup>-1</sup>)

<u>Run No.</u>	<u>Methanator Temperature (°F)</u>	<u>Percent Carbon Monoxide</u>	
		<u>Upstream</u>	<u>Downstream</u>
42	620	5.2	zero
43	420	1.25	"
44	780	5.0	"
50	580	7.5	"
50	580	9.0	"
52A	750 - 900	12.0	"
52A	"	11.0	"
52A	"	6.2	"
52A	"	3.1	"
52A	"	1.7	"
52A	"	0.8	"
52A	"	0.6	"

#### 4.2.13 Hydrogen Filter

Carbon carryover is prevented in the ADM design by operating the thermal crackers below 1600°F wall temperature (see Section 4.2.5). However, a small lightweight filter is incorporated for protection of the hydrogen flow components should a malfunction occur in the thermal crackers. Two such filters, one downstream of each reactor are provided in the ADM design.

#### 4.2.14 Cracker Air Blower

The cracker air blower must be capable of satisfying the following two flow conditions based on the design pressure drop of the Advanced Development Model Design.

	<u>Flow</u>	<u>Δ P</u>
Start-up*	1800 scfh	20 in H <sub>2</sub> O
Run	360 scfh	10 in H <sub>2</sub> O

\*Both reactors starting simultaneously.

Instrumentation and piping losses unique to the breadboard system required a blower capable of developing approximately 4 psi at the above flow rates.

For the breadboard a Dresser Industries, Roots type; Model 1701, positive displacement blower was selected. This blower was driven by a RAE Model 7873, 24 VDC permanent magnet motor. Air flow to the thermal cracker could be controlled by varying motor voltage.

For the ADM Design a thin wheel, radial blade, centrifugal blower was selected (IMC Magnetics Model BC-24-29B\*.) Two speed operation is provided by a dual winding in the integral motor. This unit is available to the appropriate military specifications.

#### 4.3 Power Conditioner

##### 4.3.1 Background - Regulator Types

An investigation of power conditioning schemes has shown that three possible regulatory arrangements are feasible: A series, step-up, or step-down regulator. These are shown schematically in Fig. 21.

In the series regulator, (A) the voltage of the fuel cell is used to power the operating load as well as the load terminals of the unit. The difference between the voltage produced by the cell and that desired at the load terminals is absorbed by transistor  $Q_1$ . This type regulator has no ripple, has excellent regulation, and has no radio interference. The circuitry is simple and straightforward and can be made very reliable. A disadvantage is low efficiency due to the high power lost in the series transistor ( $Q_1$ ) which operates as a rheostat.

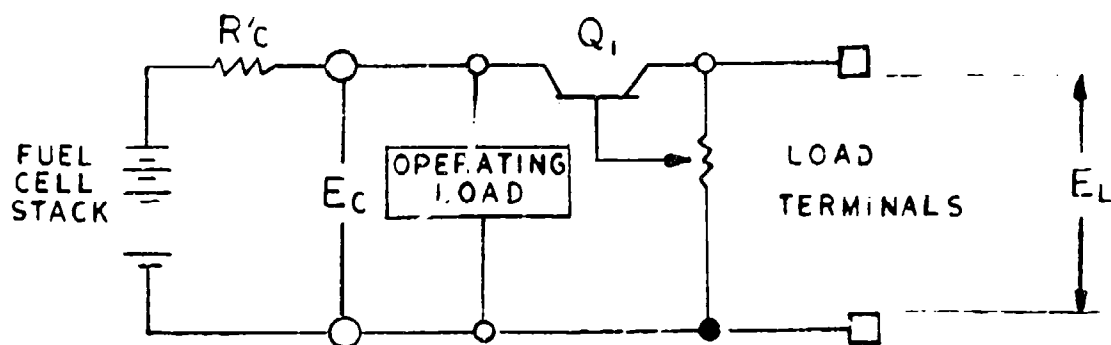
The switching regulators each offer improved efficiency over the series type.

The step-up regulator (B) functions by switching inductor  $L_2$  from a parallel to series connection with the output of the fuel cell. In the step-up regulator the continuous current which flows from the fuel cell and in the inductor  $L_1$  is greater than the load current by the ratio  $E_L/E_C + \text{Loss}$ . During the time transistor  $Q_2$  is switched into conduction, all of the fuel cell current passes only through the inductor, and the load current is entirely supplied by capacitor C.

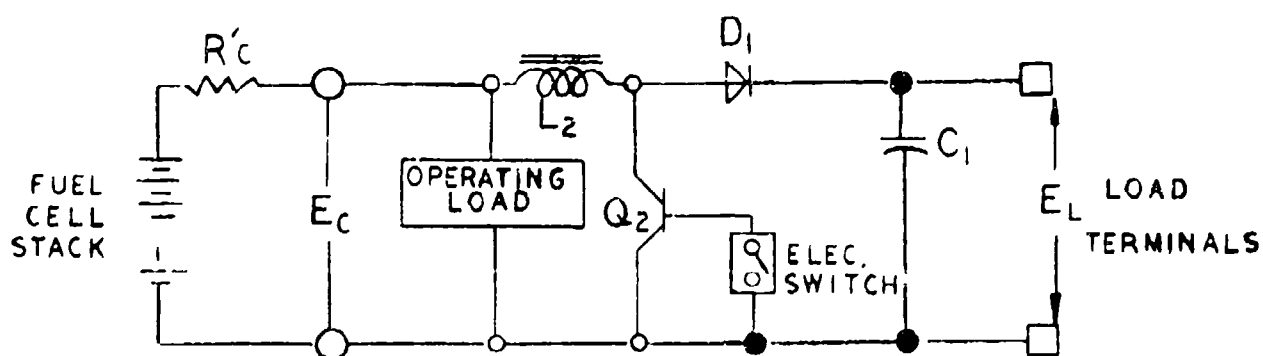
When  $Q_2$  is non-conducting the current supplied by the fuel cell and  $L_1$  divides, with a portion going to the load and the remainder recharging  $C_1$ . The load voltage  $E_L$  is controlled by the switching interval of transistor  $Q_2$  such that the boost voltage generated is related to the conduction of  $Q_2$  by the approximate ratio:

$$\frac{E_L - E_C}{E_C} = \frac{Q_2 \text{ on time}}{Q_2 \text{ off time}}$$

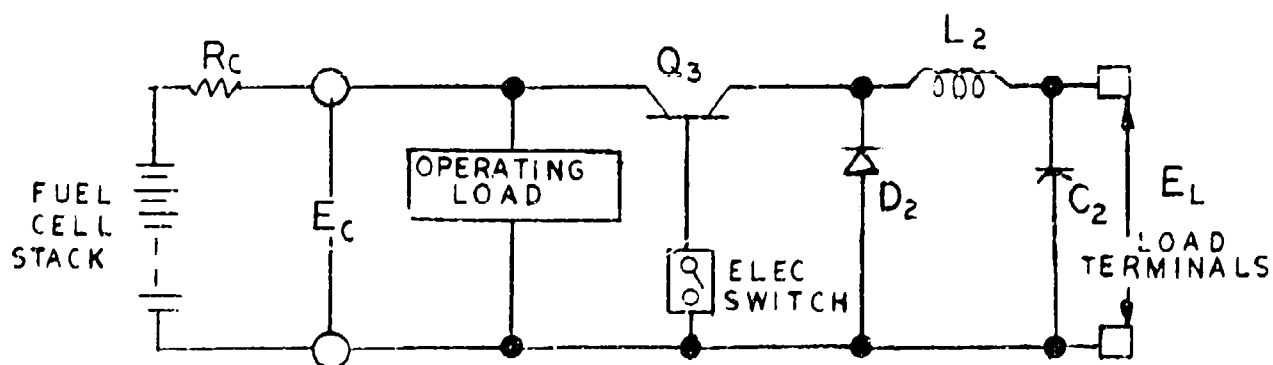
At 50 to 60 amperes this circuit requires a large value for  $C_1$  and imposes ripple currents on  $C_1$  which are greater



(A) SERIES REGULATOR



(B) STEP-UP REGULATOR



(C) STEP-DOWN REGULATOR

POWER CONDITIONER TYPES

FIG. 21

#### 4.3.1 Cont.

than the load currents. This mode of operation greatly increases capacitor failure rate.

The step-down regulator (C) operates by periodically connecting the fuel cell to the filter  $L_2C_2$ . Current from the fuel cell flows in pulses. The average current is equal to the load current and the percentage on time equals the percentage reduction in fuel cell voltage to load voltage (neglecting losses).

To compare the merits of the three electronic regulatory schemes, they were examined in relation to actual fuel cell operation.

The operating load (parasitic power) including battery charging power requires 115 watts of power which will be provided at an overall efficiency of 75%, representing a constant load of 150 watts on the fuel cell, regardless of the electrical load on the overall unit.

When the fuel cell is designed to operate into a series regulator circuit then the cell must deliver at least 35 volts to provide 34 volts at the load terminals under "end of life" conditions and allow a 1 volt drop in the regulator circuit. In the series regulator the full load current is imposed on the fuel cell. In the design for a full load current density of 150 ASF at the 26 volt, 57.8 amperes, 1.5 KVA rated output, including the 150 watt operating load, and at the same time requiring that the cell achieve 35 volts at the 34 volt, 48.6 ampere, 1.65 KVA load, at "end of life" conditions, it is determined that the fuel cell stack must consist of at least 53 cells. These 53 cells have an equivalent circuit of a 48 volt battery with a 0.16 ohm internal resistance under "new" conditions. Their internal resistance increases to 0.23 ohm at "end of life" conditions.

The total electrical power loss of the energy developed by the cell stack lies in three categories:

- A - Auxiliary power
- B -  $I_2R$  loss in fuel cell stack
- C - Regulator losses.



#### 4.3.1 Cont.

These losses are plotted in Fig. 22, and added to indicate that the series regulator loses a total of 670 watts powering a 34 volt, 1.5 KVA load and 1290 watts with a 26 volt rated load.

The switching regulators have power losses characterized by the relationship:

$$P_{SW} = P_0 + 1 \times I_L^2 R_R$$

where  $P_{SW}$  = Total regulator loss

$P_0$  = 40 watts operating circuit power  
including transistor drive

$1 \times I_L$  = transistor and diode loss of  
1 volt at load current,  $I_L$

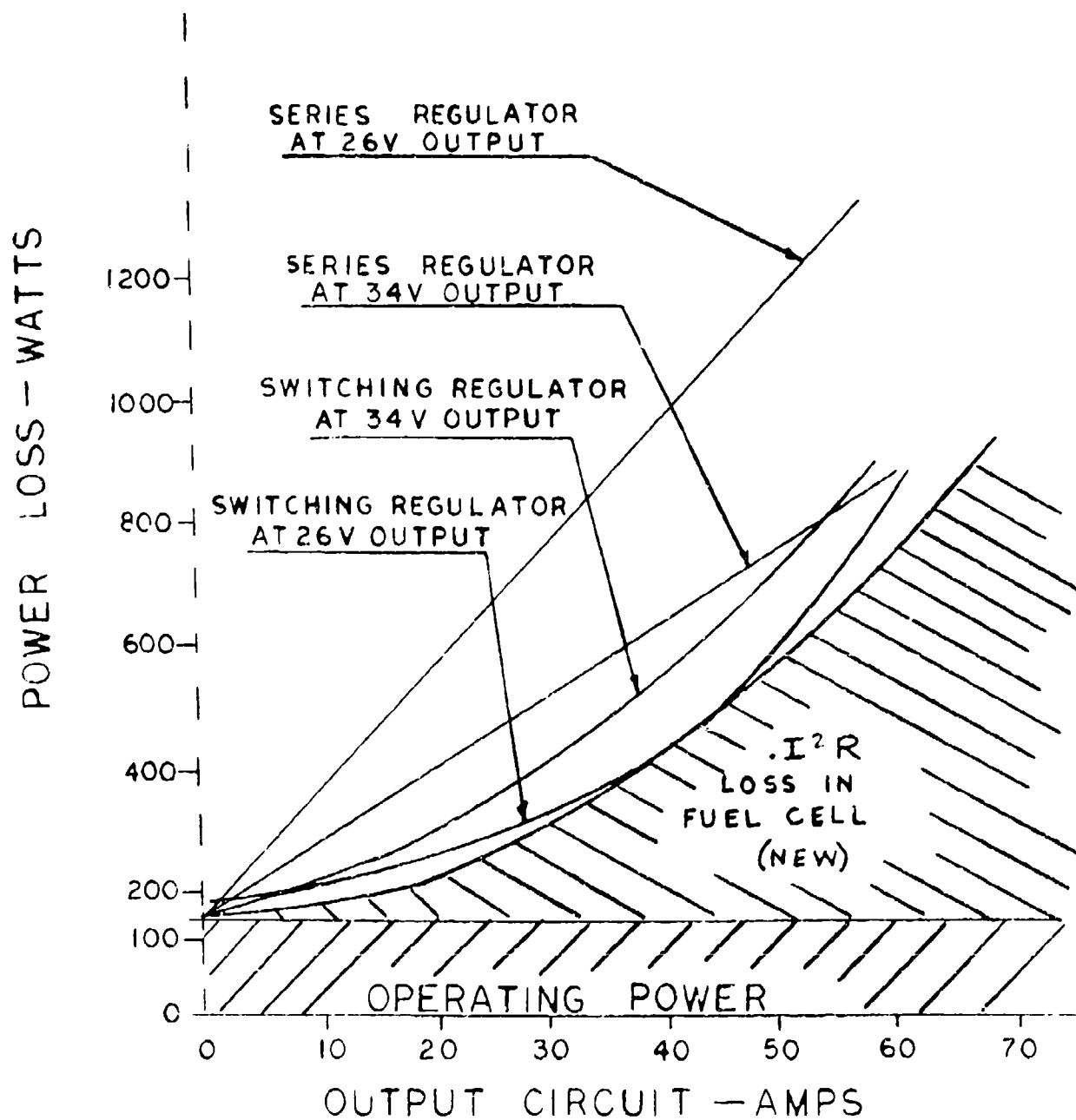
$R_R$  = circuit wiring resistance including  
ammeter shunt

When the same fuel cell stack designed for the series regulator is used for the step-down switching regulator, a marked reduction in power loss with load is achieved. This comes not only from the higher efficiency of the regulator but also from a reduction in the  $I^2R$  loss in the fuel cell. When the regulator is producing rated load at less than fuel cell stack voltage, the regulator will cycle to connect the cell to the load only part of the time. The  $I^2R$  loss in the cell is reduced in direct proportion to the cycle time.

This results in a slight increase in total power losses at the lower voltage outputs. The step-down regulator-fuel cell combination has a total power consumption of 600 watts at the 34 volt, 1.5 KVA output and 730 watts at the 26 volt 1.5 KVA output as in Table 8:

TABLE 8

	<u>Regulator Power vs Load</u>	
	<u>34 V 1.5 KVA</u>	<u>26 V 1.5 KVA</u>
Auxiliary Power	150	150
Cell $I^2R$ Loss (new)	305	382
Regulator	<u>145</u>	<u>198</u>
Total	600 watts	730 watts



# POWER CONDITIONER — POWER REQUIREMENTS

FIG. 22

#### 4.3.1 Cont.

Another advantage of a switching type regulator is that early in the stack life when the stack voltage is high the regulator takes power from the stack at an average current density lower than that required by a series regulator. This reduces fuel consumption of the new unit and also tends to prolong fuel cell life. Studies have shown that the basic cell decay is reduced by a reduction in current density.

The step-up switching regulator seems to offer advantages in stack design since fewer cells are required and the manufacturing costs would be less. However, current regulation cannot be achieved without a change in the mode of regulation from step-up to step-down, since current regulation and ripple must be achieved at output voltages of 14V or less in the current limited mode. This type of step-up regulator is not considered further due to the circuit complexity.

#### 4.3.2 Step Down Regulator Design

A more fully developed schematic of a step-down regulator is illustrated in Fig. 23.

Both the output voltage and current are continuously sensed. The voltage is regulated to a set value between 26 and 34 volts at any current up to the limit set on the current adjustment. The maximum (100%) current output is a variable dependent upon the voltage setting, and is also adjustable down to 20% maximum. Once current limiting occurs the terminal voltage is reduced and the current is regulated until the overload region is reached. The overload region occurs at terminal voltages of less than 14 volts. When the plant is operated at "overload" an all magnetic circuit breaker is tripped through a relay trip coil thereby disconnecting the load from the plant.

When a battery is connected with opposite polarity to the load terminals the regulator rapidly proceeds from voltage regulation, to current regulation, to overload. As soon as current limiting is reached, Q4 disconnects the fuel cell from the load and the LC filter circuit, so that no damaging current is forced through the cell. Tripping time of the breaker is less than 10 milliseconds at all specified ambient temperatures. During this time, fault current will build up through D3 at a rate controlled by L3, so it is necessary to size D3 with adequate fault current capability (e.g. 1,000 amperes). The circuit breaker also has conventional current trip coils set at 125% maximum current to serve as a back up in the event the "overload" circuit is disabled.

The 150 watt design parasitic power load assumed in this analysis will in a final design require more than the 150 watts indicated. The DC energy will be used directly to power blowers, timers, solenoids and temperature control circuits and any pilot or status lights required for the safe operation of the unit. In addition, a portion of the DC energy may be inverted to AC required for use by motors and timing devices.

The advanced development model power conditioner design employs silicon switching transistors in a step-down regulator to obtain the required regulation, ripple, no load and current limited operational mode. Thyristors(SCR;s) offer

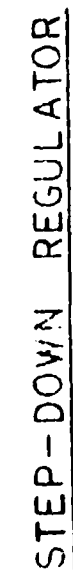
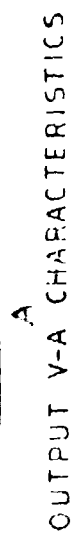


FIG. 23

#### 4.3.2 Cont.

advantage only in current handling capacity and present circuit problems in commutation (turn-off) holding current and rate of reapplied blocking voltage.

The use of a silicon power transistor as a switching element was enhanced by the availability of a special device developed by Westinghouse Electric Corporation, Semiconductor Division. This transistor is designed to have very low voltage drop in the "on" condition and high current handling capability.

Inasmuch as the power switching transistor is the most critical element in a switching regulator, a breadboard mockup of the power conditioner output circuit was assembled. It incorporated the Westinghouse transistor (Westinghouse P/N 1401-0825) and was run into a dummy load from the output of a prototype fuel cell. Total running time was in excess of 3 weeks continuous operation at current levels approximating the maximum operating levels proposed for the final design (50 to 60 amperes).

Although the switching transistor was not operated in a closed-loop regulator circuit it was run at a rate of 1 kilohertz and a varying duty cycle approximating the type of service it would see in the final design. On one occasion during operation, an overload was experienced which faulted two 60 ampere fuses without resultant damage to the switching transistor. Measurements made of saturation voltage during operation at current output levels of 60 amperes showed a drop of less than 0.12 volts.

Switching time measurements made at the 60 ampere level showed a maximum recovery time from saturation of less than 6 microseconds without the benefit of reversed polarity drive. Both saturation voltage and switching time were measured on a Tektronix Model 547 Oscilloscope.

#### 4.3.3 ADM Power Conditioner Design

The Power Conditioner is designed to meet the functional requirements expressed in the USAMERDC purchase description of 23 January 1970 and Engelhard Minerals & Chemicals Corporation technical proposal of 16 April 1970 as amended.

Fig. 24 depicts the power conditioner system in block diagram form. The power conditioner is basically a series switching step-down regulator which is operated at a clock rate of 1 kilohertz and a varying duty cycle. Appropriate circuits are provided for voltage regulation, current limit and overload. In addition, current/voltage tracking is provided so that maximum power output is held at the 1.5 kilowatt level throughout the output voltage range of 26 to 34 volts. Current and voltage overload functions include over current cutout, over voltage cutout and under voltage - over current cutout.

An inverter and regulator section furnishes the operational power necessary to run the various functional circuits of the power conditioner. Voltage regulation and current protection where required, is provided by integrated circuit regulators.

A battery charger section incorporates both current and voltage regulation and provides a constant current charge up to a pre-set terminal voltage limit which is temperature corrected. The charge rate is limited to ten percent of the ampere-hour rating of the battery.

The functional blocks shown in Figure 24, are detailed in individual drawings which will be described in the following:

##### 4.3.3.1 Switch

The switch consists of a special silicon power transistor manufactured by Westinghouse Electric Corporation. It was developed to exhibit extremely low  $V_{ce}$  (SAT), (typically 0.1 volts at 75 amperes). It has high collector current capabilities, (250 amperes) and maintains high current gain at high current levels, (typically 40 to 80 at 75 amperes). In





#### 4.3.3.1 Cont.

function the switch transistor switches the output of the fuel cell to the output filter at a rate of 1 kilohertz. The on-off time ratio is automatically adjusted by the current/voltage control circuitry so that the integrated output of the Output Filter remains within the required current and voltage control parameters, as described in section 4.4.

#### 4.3.3.2 Output Filter

The output filter is comprised of a commutating diode, a filter inductor and a filter capacitor. The function of the output filter is to integrate the variable duty cycle current pulses from the switch into a low ripple D.C. voltage at the output terminals of the power conditioner. The commutating diode provides unidirectional current flow through the inductor to the filter capacitor when the switch opens and the stored energy in the inductor causes its terminal potentials to reverse. The diode also protects the output transistor in the switch from reverse polarity in the event the power conditioner is improperly connected to a source of reverse potential such as a battery bank.

#### 4.3.3.3 Driver

The driver consists of 4 stages, the last two of which are a complimentary symmetry pair. The driver supplies drive current to the switch at a level of approximately 5 amperes.

The input signal to the driver comes from the schmitt trigger. The function of the schmitt trigger is to provide an on-off signal which is amplified by the driver and applied to the output stage or switch in order to assure that the switch is either in saturation or off.

#### 4.3.3.4 OR Gate

The OR gate accepts any of four command signals and its output controls the schmitt trigger. In effect the OR gate selects the mode of operation of the output switch, i.e. voltage limit mode, current limit mode, or overload in addition to supplying a commutating pulse at the beginning of each millisecond period.

#### 4.3.3.5 Voltage Integrator and Current Integrator

The voltage integrator and current integrator perform similar functions. Input signals come from voltage sense and current limit and consist of DC signals representing output voltage and current levels. To these signals are added internally generated synchronous saw-tooth waveforms. The result is a ramp and pedestal waveform which when fed through the OR gate is used to control the schmitt trigger.

#### 4.3.3.6 Clock and Discharge

The clock and discharge provides the 1 kilohertz main time base for the power conditioner. It also discharges the sawtooth integrator capacitors in the voltage and current integrators at the beginning of each 1 millisecond period.

#### 4.3.3.7 Voltage Sense

Voltage sense is a comparator which compares the output voltage of the power conditioner with an internal standard voltage. Any difference between these potentials generates an error signal which is amplified and sent to the voltage integrator to control the output of the power conditioner in such a way as to reduce the difference. Adjustment of the output voltage of the power conditioner is obtained by means of an adjustable divider from which the output voltage is sampled.

#### 4.3.3.8 Current Limit

Current limit is a comparator which functions to provide adjustable, power conditioner output current limit. In addition a current/voltage tracking function is included so that the maximum fuel cell power output (product of current and voltage) remains at the 1.5 kilowatt level throughout the adjustable output voltage range of 26 to 34 volts. The output of the Current Limit is an amplified error signal representing the difference between the current limit setpoint and the actual fuel cell power conditioner output current. When the output current exceeds the pre-set limit, the error signal is of such a polarity and magnitude to cause the current integrator to act through the OR gate controlling the schmitt trigger and therefore the output current of the power conditioner.

#### 4.3.3.9 Current Sense

The current sense is an amplifier which amplifies the 50 millivolt shunt signal to a usable value for application in the current limit and overload functions.

#### 4.3.3.10 Overload

Overload operates to shut down the power conditioner under certain overload conditions as follows:

##### 4.3.3.10.1 Over Voltage

If the output voltage of the power conditioner should rise above a pre-determined point which is several volts above maximum output level, shut down will occur by means of circuit breaker trip and electronic shutdown. This over voltage condition may result from either over voltage output from the power conditioner or through connection of the power conditioner to a high voltage load such as a battery bank.

##### 4.3.3.10.2 Over-Current and Under-Voltage

Under conditions of heavy loads where the power conditioner operates in the current limiting mode and power conditioner output terminal voltage drops below 14 volts, shutdown will occur.

##### 4.3.3.10.3 Polarity Reversal:

Instantaneous polarity reversal at the power conditioner output terminals such as might be caused by improper connection to a battery bank load will also cause shutdown.

When shutdown occurs as in the above-mentioned cases, the overload indicator light will be activated and it will be necessary to depress the reset switch and reset the circuit breaker before output from the power conditioner can be obtained. These shutdown functions are obtained through electronic sensing and are backed up by the normal trip function of the circuit breaker.

#### 4.3.3.11 Circuit Breaker

The circuit breaker consists of a three pole companion trip unit which meets the requirements of USAMERDC drawing 13208E8540 with the exception of the addition of the third pole which functions as a relay-trip pole operated by the overload section of the power conditioner. The two poles in the output lines of the power conditioner employ conventional series trip coils. Provisions are made to power the relay trip for overload conditions by means of the stored charge in an electrolytic capacitor which is charged by either the output of the power conditioner or an internal 15 volt supply, whichever is greater.

#### 4.3.3.12 Filter

The RFI filter consists of two enclosed, tubular, hermetically sealed PI section networks. Attenuation characteristics are essentially a straight line from 25 db at 14 KHz to 80 db at 150 KHz and greater than 80 db from 1 MHz to 10 GHz when plotted semi log with frequency on the log scale.

The input filter consists of a bypass capacitor which provides a low impedance path for switching transient spikes to limit peak voltage across the power switching transistor.

#### 4.4.1 Fuel-Air Control System

##### 4.4.1.1 Background

A thermal cracker fuel cell power plant requires a control system to provide the necessary timing for cracker sequencing, valve operation and fuel and air regulation.

Two thermal crackers are employed in the breadboard fuel cell power plant. They are operated alternately in purge/crack and burn-off modes so that a supply of hydrogen is constantly available for use in the fuel cell. The basic cracker cycle is 6 minutes long and consists of 3 modes, namely purge (30 seconds), crack (3 minutes) and burn-off (2-1/2 minutes maximum). This cycle is shown graphically in Fig. 19.

In order that the power plant system can operate in a fuel conservative manner it is necessary to provide a variable fuel flow rate which is controlled by the output load demand. This necessitates a controlled burn-off period to establish the proper oxygen-carbon ratio for burn-off. Too little oxygen will leave excess carbon in the reactor and overheating or oxidation of catalyst.

The fuel-air control system used on the breadboard fuel cell power plant is comprised of two principal functional elements; the burn-off air control and the fuel rate controller. The burn-off control is designed to provide a constant fuel to burn-off air ratio over a variable fuel rate of from 1 to 3 pounds per hour. The fuel rate controller in turn controls the fuel flow to the cracker in response to a demand signal generated by the fuel cell.

Central to both control elements are the fuel pumps. The pumps used are modified Bendix Model #480527. The modifications provide a constant fuel output per pulse. Fuel flow rate is thereby controlled by varying the pulse frequency and total mass flow is detected by "totaling" the number of pulses over each complete pumping cycle.

##### 4.4.1.2 Burn Off Air Control

The cracker burn off air control system consists of

#### 4.4.1.2 Cont.

two fuel rate integrators and the comparator and blower motor control. The fuel rate integrator receives an input signal from the fuel pump rate controller. The integrator, which is discharged at the beginning of each purge (and crack) cycle receives one impulse for each fuel pump plunger stroke. For each impulse from the pump, a small charge is run into the integrator capacitor, each incremental charge increasing its terminal voltage by an equal amount in such a manner that at the end of the crack period, the voltage stored in the integrator represents the analog of the total flow through the pump. During the burn-off period the integrator is discharged at a constant rate (disintegrate".) This constant discharge rate then determines how long the blower remains on during burn-off because discharge time at a constant rate is determined by total discharge required to reach the pre-set arbitrary discharge potential.

The comparator and blower motor control accepts the signal output from the integrators during their respective burn-off period and determines whether the integrator potential is above the pre-set "shut-off" potential. When this potential is reached the blower is turned off by the output relay thereby providing a burn-off time directly proportional to the total quantity of fuel pumped during the preceding purge and crack cycles.

#### 4.4.1.3 Fuel Rate Controller:

The fuel rate controller consists of the fuel cell demand detector, and two fuel pump rate controllers.

The fuel cell demand detector operates as a comparator with a variable set point which represents the desired fuel cell stack voltage. Difference between this setpoint and stack voltage as sampled from the last three cells generates an error signal which regulates the fuel pump rate.

The fuel pump rate controller is a variable rate impulse generator which actuates the solenoid coil of the final pump either at the variable rate as demanded by the

#### 4.4.1.3 Cont.

fuel cell demand detector, or at a predetermined fixed rate as set by the purge rate control. The purge rate is preset to a 2-1/2 pound per hour fuel flow rate which is also that fuel flow rate used during start-up.

The overall fuel-air control system is depicted in block diagram format in Fig. 25. Functional interconnections for the various control system components are shown in Fig. 26. Simultaneous sequencing of the control elements and cracker valves is provided by means of three switches CS1, CS2, CS3 actuated by cams common to the cracker valve drive, Fig. 27.

#### 4.4.1.4 Fuel-Air Control System Development

During development, the fuel-air control system components underwent relatively minor changes. The system is shown in block diagram in Fig. 25, and the actual switching relationships related to timing and function changes are shown in Fig. 26. The switching is accomplished by relays which are in turn actuated by cam switches shown in Fig. 27.

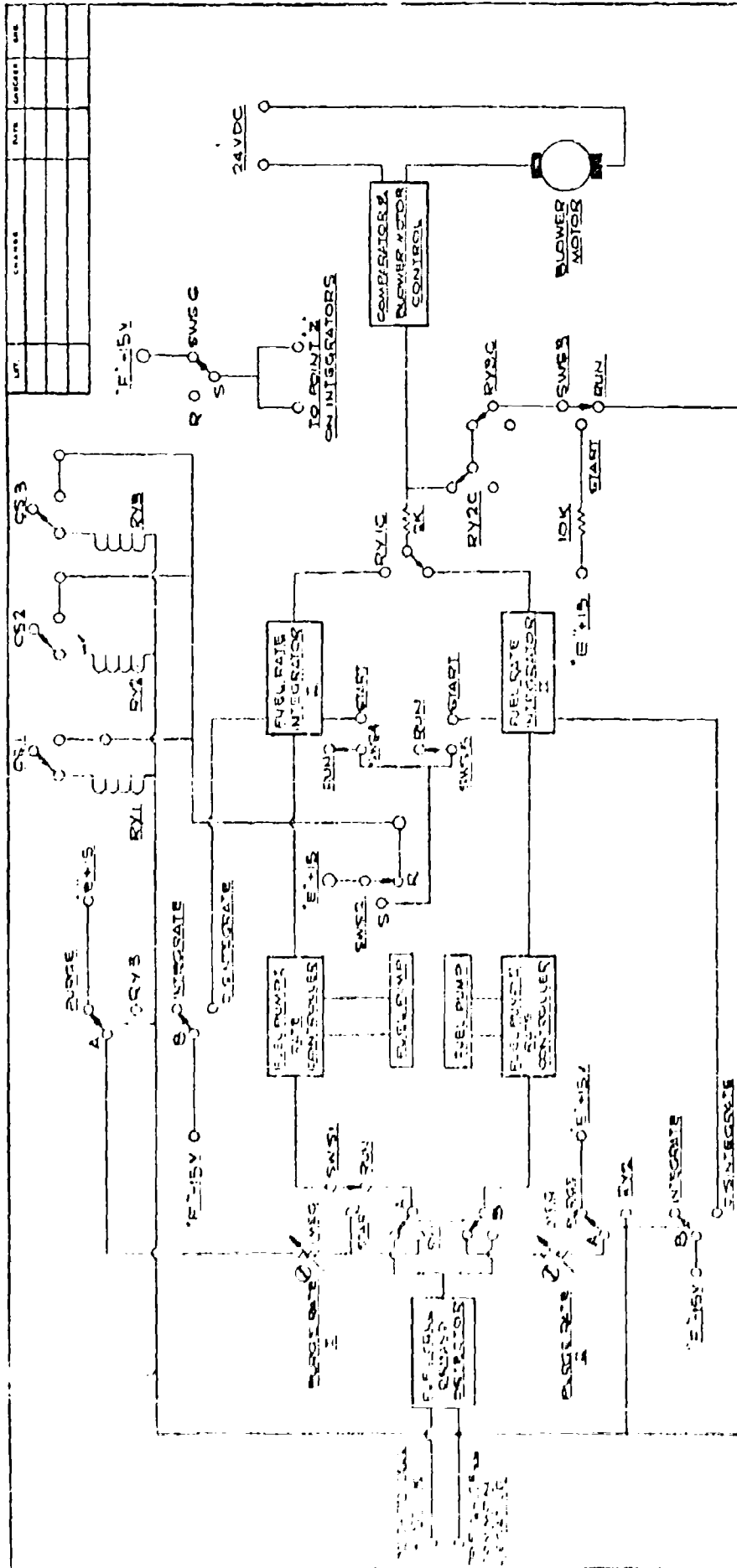
The design of the fuel cell demand detector was modified to provide a maximum pump pulse rate limit. This was found to be necessary because the fuel pumps have a maximum usable pulse rate above which output diminishes and under large demand signals may cease altogether due to the inability of the piston to respond to rapid pulses.

The fuel pump rate controller was found to be quite stable. It was necessary, however, to trim the value of the unijunction charge rate capacitor to provide identical pump pulse rates from both pump rate controllers for identical demand detector signal outputs.

The fuel rate integrators required several changes in the original design. An integrate disable function was provided so that no integrator voltage would be built up during start-up. A pulsed constant current integrator charging circuit was designed to provide linear operation over the integrator operating voltage range (0-6 volts). Special low leakage diodes for use in the integrator circuit were incorporated to reduce errors and increase storage time capability. A method

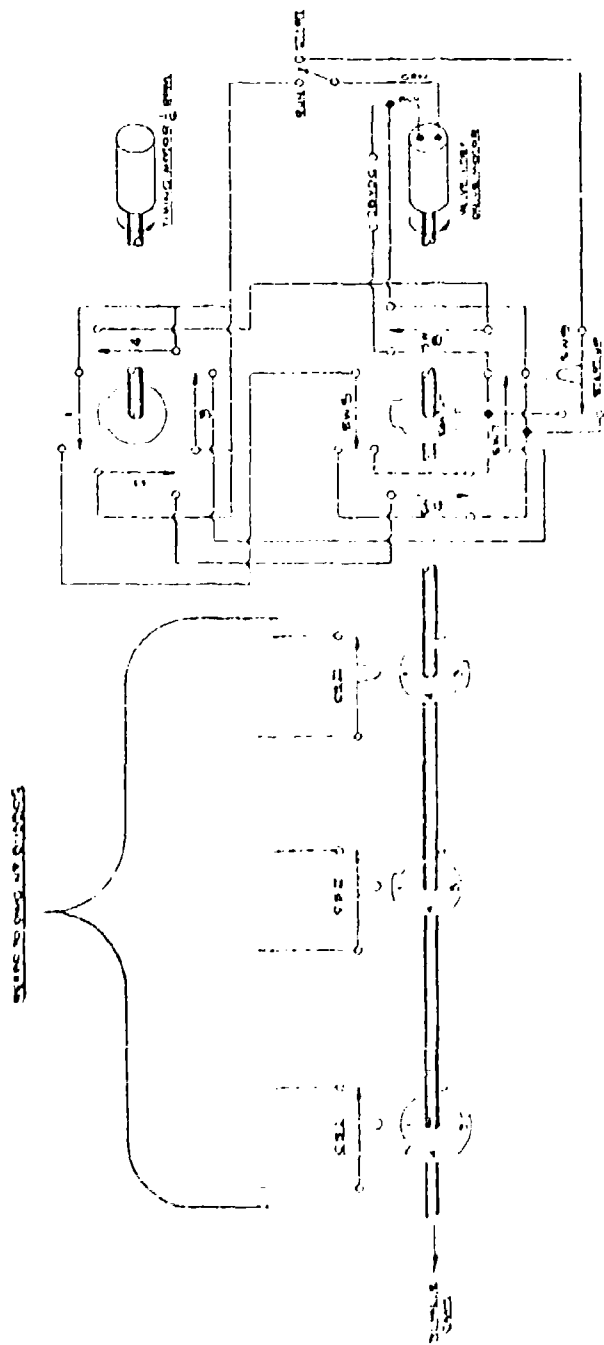






FUEL/AIR CONTROL SYSTEM SWITCHING DIAGRAM  
FIG. 26.

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CIRCUIT SCHEMATIC TIMER & VALVE ACTUATOR  
FIG. 27

#### 4.4.1.4 Cont.

was provided to assure integrator discharge during start-up.

Integrator linearity during charge and discharge cycles was determined to be within one percent and results were reproducible. At first, integrators were adjusted for an incremental charge rate of ten millivolts per fuel pump pulse, however, this was changed to approximately 30 millivolts per pulse due to the pump output per pulse. "Disintegrate" or constant rate integrator discharge was set for a rate of 40 millivolts per second.

#### 4.4.1.5 TABLE 9

Parasitic Power at Full Load

<u>Item</u>	<u>Power Watts</u>	<u>Duty Cycle %</u>	<u>Avg. Power Watts</u>
Fuel Cell Blower			
High Speed	80	75	67
Low Speed	20		
Power Conditioner I			
Inc. Battery Charger	236	100	137
Fuel/Air Control System	5	100	5
Valve Actuator	35	0.3	.1
Fuel Pumps	.6	117	.7
Central Sequence Timer	.75	100	.75
Cracker Burn-Off Blower	75	83	62
Fuel Solenoid Shut-Off			
(latching)	Negligible		Negligible
Total			272.5 (II)

#### Notes:

- A Power conditioner power consumption based on average output voltage of 30v and 8 hr battery charge rate.

#### 4.4.1.5 Cont.

- B. For some applications with varying load cycles the battery charger could automatically be deactivated during full load periods thereby reducing parasitic power at full load by 24 watts.
- C. All fuel consumption and process calculations were based on end of life single cell voltage of 0.65 volts. When new, single cell voltage will be approximately 0.70 volts. Because of the power conditioners ability to utilize this higher source voltage at a correspondingly reduced amperage while maintaining the same net system output. The gross fuel cell output has been assumed to be an average of 1750 instead of the 1772.5 presented above.

#### 4.4.1.6 Overload

The purchase description specifies that the set shall be capable of carrying 110 percent of rated load continuously at any voltage within the specified operating range, at any of the specified environmental conditions and with no change in cooling requirements, for a period of 1 hour.

All equipment except the power converter overload system as presented in the design in this report is adequate to carry 110 percent of rated load continuously at any voltage within the specified operating range, at any of the specified environmental conditions for a period of 1 hour.

Approximately 20 watts additionally are required during the overload condition for the power converter.

During the overload condition the fuel cell output must be as follows:

Delivered Power:	$1500 \times 1.1 =$	1,650 watt
Parasitic Power:	$250 + 20 =$	<u>270 watt</u>
Total Fuel Cell Output		1,920 watt

#### 4.4.1.6 Cont.

Component overload requirements are detailed below:

##### A. Fuel Requirements:

Purge	0.462 lb/hr
Product Gas	<u>2.640 lb/hr</u>
Total	3.102 lb/hr

##### B. Cracker:

The thermal cracker as presented in the design plan is large enough to operate at a fuel rate of 2.8 lb/hr which is more than the required rate of 2.69 lb/hr required during the overload condition.

##### C. Fuel Pumps:

The fuel pumps are adequate to supply the slightly higher fuel rate requirements. The fuel pumps' power requirements do not increase during the overload condition.

##### D. Carbon Combustion - Air Blower:

The same amount of air is supplied by the blower during the overload condition as is supplied for the higher fuel rate during normal operation. During the overload condition the cracker will perform under a slightly lower oxygen to carbon ratio but still high enough to prevent catalyst plugging. No additional power input into the blower is required during the overload condition.

##### E. Methanator:

The methanator as presented in the design plan is large enough to handle the slightly increased cracker product gas flowrate.

##### F. Fuel Cell:

The fuel cell is designed for an output of 1920 watts.

4.4.1.6 Cont.

The overall dimensions as shown in the design plant will not change.

G. Fuel Cell - Air Blower:

The air blower output is not increased during the overload period, therefore, no additional power input is required. The fuel cell will operate during the overload period at a slightly higher temperature than during normal operation.

H. Controls:

No additional power is required for controls during the overload period.

#### 4.4.2 Fuel Cell Start-Up

The operating temperature range of the fuel cell is 212°F to 350°F therefore the most severe start-up condition is at -25°F ambient where a minimum temperature rise of 237°F is required. This must be done during the 15 minute start-up period. The amount of heat required during this period is approximately 1900 Btu's not including any heat losses.

In developing a workable start-up system, four methods for heating the fuel cell were considered:

A. Heat Exchanger:

The hot combustion gases from the thermal crackers flow through one side of a heat exchanger. On the other side a blower would force heated air to the fuel cell.

B. Integral Heat Exchanger:

In this case a heat exchanger would be built into the lower part of the thermal crackers. Air would flow through the exchanger and then to the fuel cell to provide heat.

C. No Heat Exchanger:

The reactor is brought to a higher than normal temperature, fuel flow is stopped and air is blown through the cracker to the fuel cell. Initially it would be necessary to mix the hot air with cooler air before entering the fuel cell.

D. Separate Start-up Burner:

In this method, a separate start-up burner is used to supply hot combustion gases to a heat exchanger. Air is blown through this heat exchanger and then into the fuel cell by the fuel cell blower. Hot combustion gases are not fed directly to the fuel cell since impurities in the combustion gases could adversely affect the fuel cell.

#### 4.4.2 Cont.

Each of the four systems was theoretically evaluated and all advantages and disadvantages were tabulated.

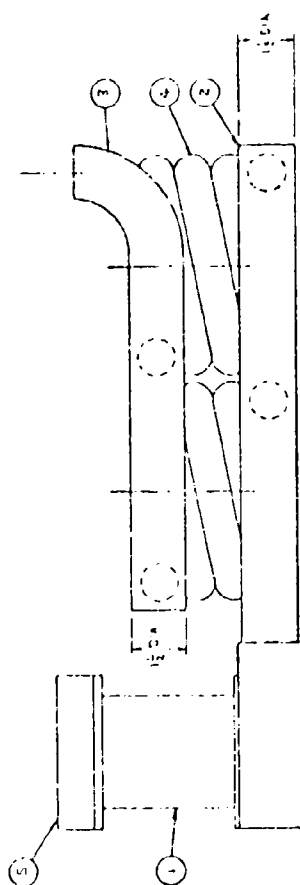
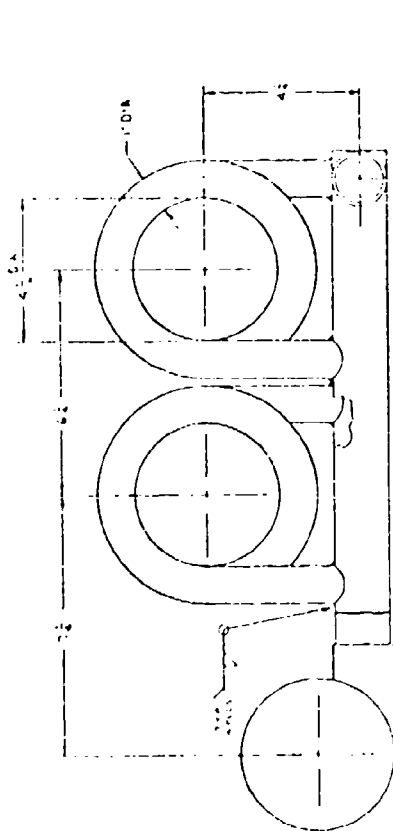
	<u>Advantages</u>	<u>Disadvantages</u>
<u>Sep. Heat Ex.</u>	Nothing added to thermal crackers.	Inadequate heat transfer. Large size.
<u>No Heat Ex.</u>	Lightweight. Does not add much to piping, controls, simple.	Inadequate heat transfer.
<u>Int. Heat Ex.</u>	Heat supplied is adequate.	May cause reactor to overheat. Control system not simple.
<u>Sep. Burner</u>	Abundant heat supplied.	Heavy, bulky, most costly.

Based on the tabulation and the heat transfer calculations a coil wrapped around the bottom section of the thermal cracker was chosen as the fifth and optimum method for supplying heat to the fuel cell. The coil would consist of a 1" O.D. tube wound 4 times around the thermal cracker. (See heat exchanger assembly, Fig. 28.) Each reactor would have a coil wound around it. The surface area per coil is approximately 1-1/4 square feet so that the total surface area is 2-1/2 square feet. The heat transfer coefficient outside coil was calculated to be approximately 8 based on radiation and convection. The coefficient for the air flowing inside the coil was also calculated and correctly for flow in a helix.

A heat exchanger coil was attached to one of the breadboard thermal crackers with a thermocouple in the outlet air stream. Temperature data was taken from a cold start-up and this was plotted on Fig. 29. The heat transfer coefficient determined from this data is about 6-8. This is close to the calculated value which was based on temperature data shown on Fig. 30 from thermocouple locations as pictured on Fig. 31. The calculations show that not enough heat would be transferred to heat up the fuel cell in the required time. A shield around

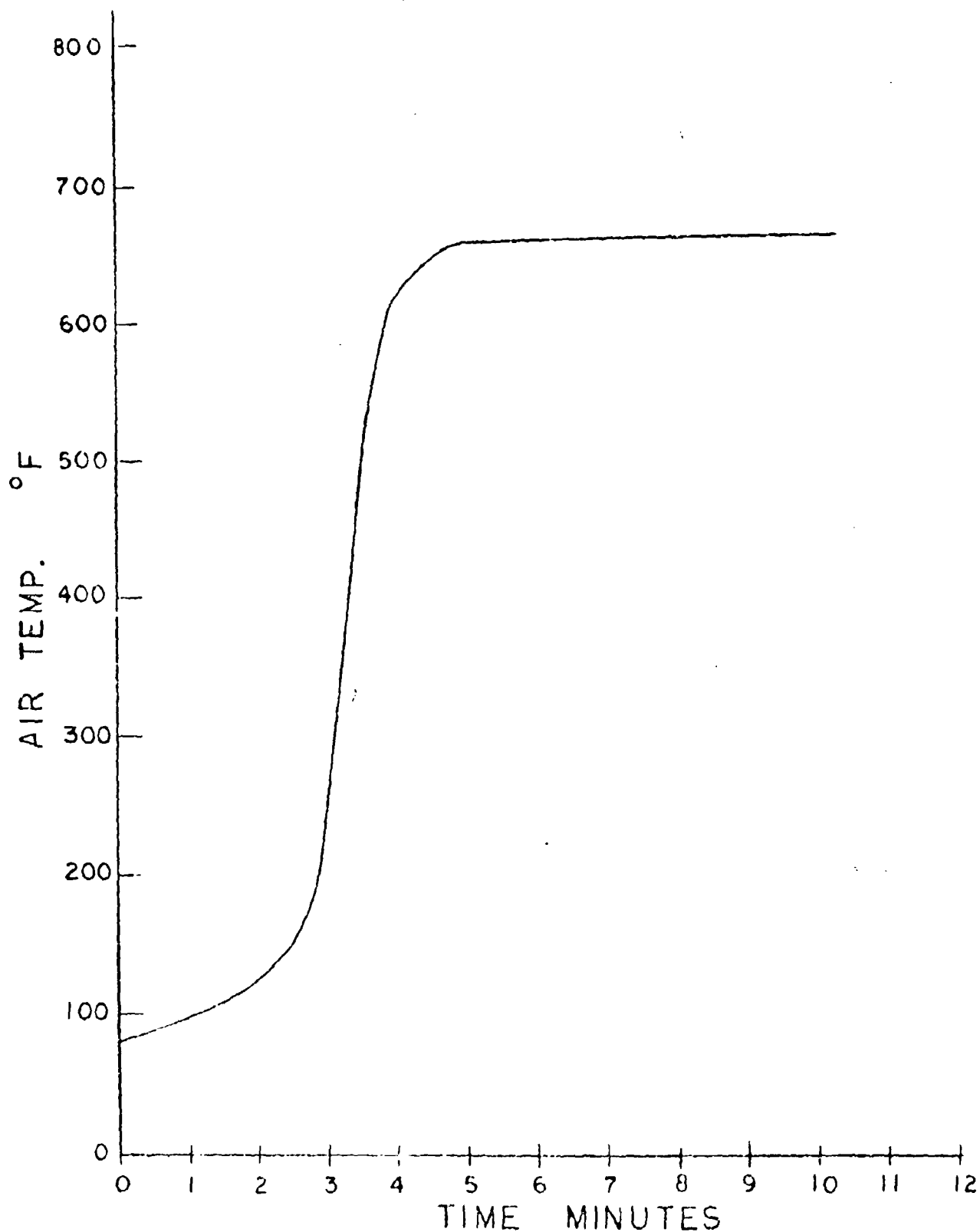


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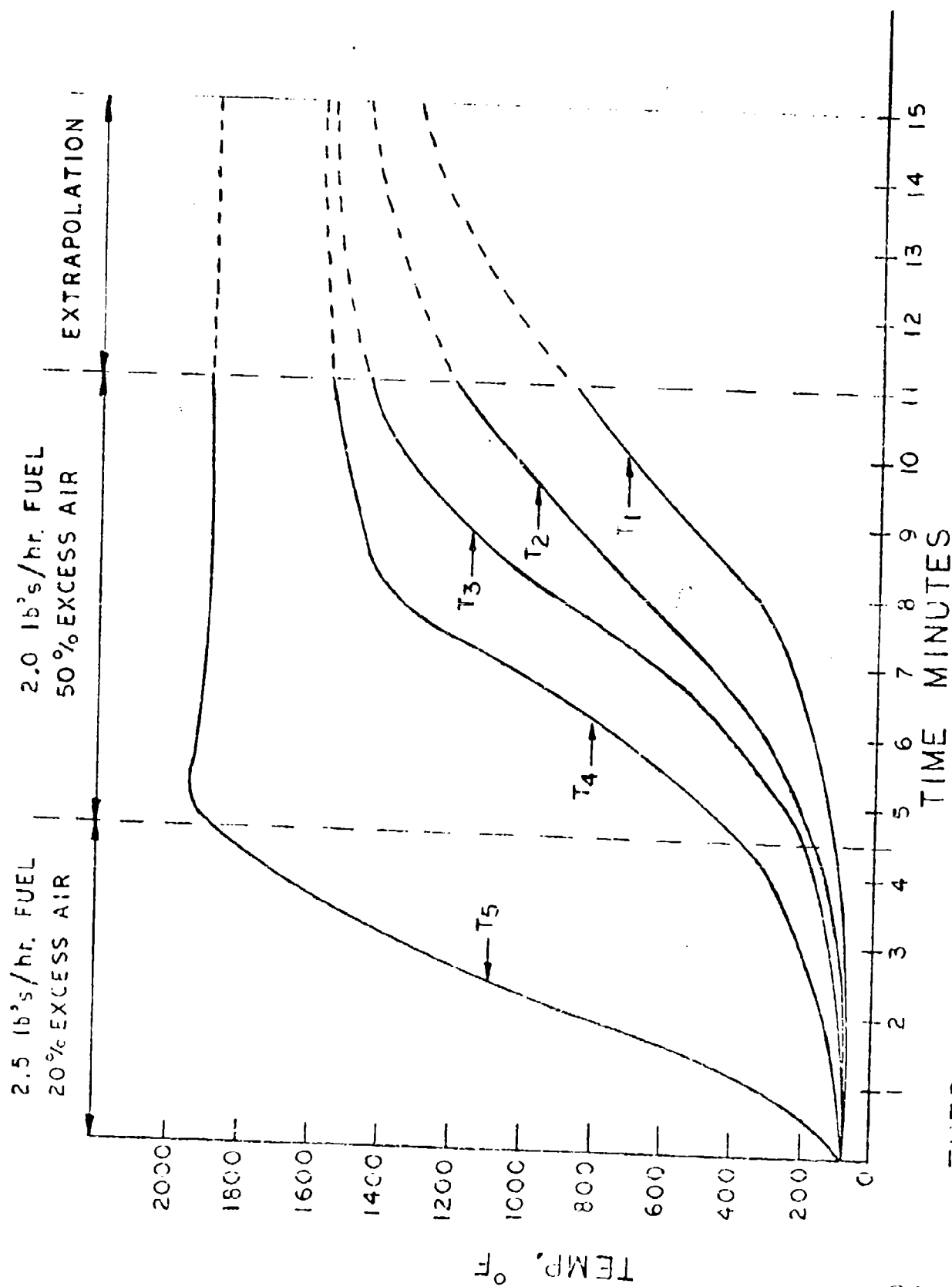
HEAT EXCHANGER ASSEMBLY  
FIG. 28



TEMPERATURE OF AIR LEAVING HEAT EXCHANGER

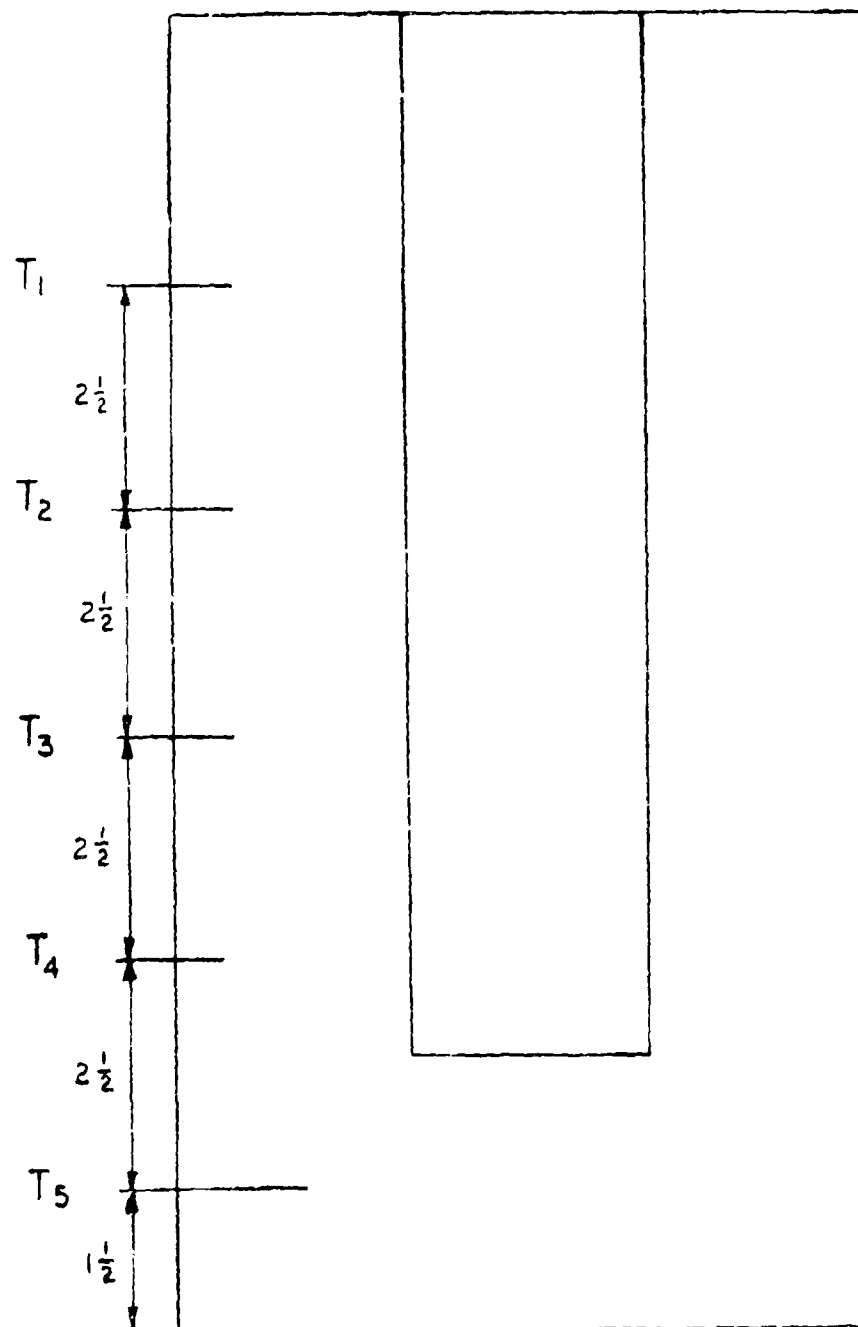
FIG. 29

-85-



THERMAL CRACKER, START UP TEMPERATURE PROFILE

FIG. 30



THERMOCOUPLE LOCATIONS

#### 4.4.2 Cont.

the tubing would change the radiation view factor and increase the efficiency of the heat transfer. The heat transferred would be approximately 4800 Btu's in fifteen minutes. The heat lost through the insulation and to sensible heat is about 2700 Btu's in fifteen minutes thereby leaving about 2100 Btu's to heat the fuel cell. The time required for heat up would then be 13-1/2 minutes, since only 1900 Btu's are required to heat up the fuel cell to operating temperature.

The air leaving the heat exchanger could reach a temperature of 600 to 700°F, it would therefore, have to mix with air supplied by the fuel cell blower in order to prevent localized over-heating of the fuel cell. The fuel cell temperature controller mentioned previously will be used to control the diluent air supply. A separate blower would provide air flow through the two coils at a rate of 10 scfm per coil. The pressure drop would be approximately 4 in. W.C.

#### 4.4.3 Start-Up Battery

Electrical power is required to operate ancillary equipment during the 15 minute start-up period. This power in the ADM design is provided by a rechargeable battery pack. The battery pack is recharged during normal system operation. (Battery charging operation is described in section 4.3.3.) This battery pack consists of 28, 6.5 ampere hrs capacity, sintered-plate, nickel-cadmium vented cells. These cells have a filled weight of 9.1 oz each, thereby giving a battery weight of 16 pounds excluding enclosure.

Parasitic power requirements during a fifteen minute start-up period are as follows:

Igniters	240 watt-minutes
Cracker Air Blower	4120 watt-minutes
Fuel Cell Blower	350 watt-minutes
Heat Exchanger Blower	1300 watt-minutes

At an average per cell voltage during discharge of 1.1v average battery voltage would be 30.8 volts and a battery capacity of 3.3 ampere-hrs would be required. The cells chosen for this application have a nominal capacity of 6.5 ampere-hrs at 70°F. At the actual discharge rate during start-up (approximately four times nominal discharge rate) is reduced to 5.2 ampere-hrs. At minus 40°F capacity is further reduced to a range of from 2.6 to 3.7 ampere-hours. Manufacturers data generally does not recommend the use of nickel-cadmium batteries below a temperature of minus 40°F (Ref. 1). For arctic conditions (-40°F to -65°F), a supplementary battery pack or active thermal control of the battery would be required.

#### 4.4.4 Advanced Development Model Packaging

The ADM alyout is shown on Fig. 32. The following are comments on specific design areas.

##### 4.4.4.1 Frame

The frame design calls for 6061 aluminum structural shapes and 6063 extruded squares. The frame will be of all welded construction. The roll bars will be bolted to the frame to allow for removal for maintenance. After welding, the frame and roll bars will be heat treated to a T6 temper.

Aluminum has been chosen on the basis of a comparison with steel of their relative energy absorbing capacities in impact and damping capacities for vibration control. Energy abosrbing capacities can be compared by using the equation.

$$u = \frac{\sigma_y^2}{2E}$$

Where u equals the energy a material can absorb per unit volume when it is stressed to the proportional limit,  $\sigma_y$  = yield stress and E = modules of elasticity. As can be seen aluminum with an E 1/3 of steel and a density 1/3 of steel is a good choice. However, because the yield stress is squared, this does not hold true unless the aluminum is in the T6 condition.

The frame will be designed for rigidity by designing equipment support members so that the natural frequency exceeds the test frequency. This will be done by using members with a high moment of inertia to weight ratio, the liberal use of gussets, and braces in three mutually perpendicular axes where members would vibrate as cantilevers or beams.

A reduction in design stress will be utilized in the horizontal plane to provide for fatigue loading during vibration. This will not be necessary in the vertical plane because the design for drop test will be more than adequate for fatigue.

The design for shock and vibration may require a prohibitive weight increase. It would then be necessary to





#### 4.4.4.1 Cont.

perform a trade-off study.

The frame will be anodized for protection against galvanic corrosion and will be finished per MIL-F-10472A. A single lifting eye is provided above the power plant center of gravity.

#### 4.4.4.2 Piping

Burn-off air tubing will be 1-1/2" O.D. stainless steel. Product gas tubing will be 3/8" O.D. stainless steel. Fuel line tubing from the fuel check valves to the thermal crackers will be flexible per MIL-H-13444, Type I or II. The remainder of the fuel line will be 1/4" O.D. stainless steel. Tubing from the air-preheater to the fuel cell will be 1-1/2" O.D. stainless steel. Formed tubing will be used instead of butt-welded elbows where bend radii are sufficient.

Fuel and product gas line connectors will be stainless steel SAE standard flare fittings.

A connector will be installed in the air line between the air-preheater and the fuel cell. This will be a lightweight, gasketless joint, Type J13 manufactured by Aeroquip Corp. A bellows type, thermal expansion joint will be installed in the same line.

Provision will be made at the outlet of the air exhaust valve for connection of an exhaust duct when the set is operated in a confined area.

#### 4.4.4.3 Panel

The instrument panel and the power conditioner access door will be 1/3" thick aluminum. The remainder of the instrument housing will be thin sheet with ribs attached for rigidity. The entire housing will be anodized for protection against galvanic corrosion.

#### 4.4.4.4 Safety

Two safety systems are incorporated in the ADM

#### 4.4.4.4 Cont.

design: Automatic shut-down in the event of system fault, and personnel protection.

##### 4.4.4.4.1 Safety Shut Down

Safety override and shut down is designed as an integral part of the fault detection system. In the event of a malfunction which could cause a personnel hazard, system damage or improper system operation, the system will automatically be sequenced to shut-down. During normal operation the primary shut down signal will be the inability of the thermal cracker to provide adequate hydrogen to meet fuel cell demands up to rated load. Typical failures which could cause this condition to exist are: insufficient fuel, cracker under-temperature and overtemperature, functioning of cracker over-pressure safety, auxiliary component failure, or fuel pressure failure.

Secondary shut down signals will be generated by fuel cell over and under temperature.

During the start-up portion of power plant operation, a flame safety device will monitor fuel ignition on the start-up filaments and will terminate the start-up cycle should ignition be lost.

##### 4.4.4.4.2 Personnel Protection:

Expanded aluminum metal will be used to cover a portion of the back of the set to provide personnel protection against the hot thermal crackers. A shield as described in 4.4.4.6.1 will provide protection on the top of the set. All hot gas exhausts in the ADM design are directed away from the operator.

##### 4.4.4.5 Environmental Protection

A lightweight aluminum shield will be installed on a portion of the top of the set. It will cover the valves and the thermal cracker. It is intended to protect the valve operating mechanism and conversely provide personal protection against the hot valves and thermal crackers. The

#### 4.4.4.5 Cont.

bottom of the shield will be insulated. Ribs will be attached to the top for rigidity. Protection of other items against sand, dust, or rain will not be necessary.

#### 4.4.4.6 System Weight

The weight breakdown of the ADM design is as follows:

	<u>Wt.-lbs</u>
Fuel Cell and fuel cell housing	50.0
Thermal Crackers (2)	34.0
Insulation	2.0
Storage Battery Assembly	16.5
Panel Assembly	
Panel and housing	2.5
Elapsed Time Meter	.4
Ammeter	.6
Voltmeter	.6
Circuit Breaker	.7
Power Conditioner	27.5
Electrical wiring and controls	3.0
Inlet and exhaust air valves	4.5
Hydrogen Valves (2)	.3
Fuel Check Valves (2)	1.3
Solenoid Valve	.2
Valve Cam and Motor Drive Assembly	
Cams	.3
Motor	.5
Rack	1.5
Product Filter (2)	.7
Sequence Timer	.4
Lead & Sulfur Trap & Methanator	3.9
Burn-Off Air Blower	4.0
Fuel Cell & Start-Up Air Blower (2)	7.5
Frame	16.0
Tubing & Fittings	4.3
Start-Up Air Preheater	6.0
Fuel Pump (2)	3.4
Total	<u>192.6 lbs</u>

These weight estimates are based on components as tested on the breadboard system.

## 5.0 Discussion

Further Technical Investigation Required - although the advanced development design was functionally verified by breadboard testing, several areas, primarily life effects, must be further investigated before performance of a field system can be fully characterized. These areas are summarized below.

### 5.1 Reactor Catalyst Life

The longest full size thermal cracker run performed in this program was 80 hours. Although performance at this point was satisfactory, the length of the run does not allow projection of a 1500 hr operating life. Long term catalyst life may be adversely affected by trace elements present in the hydrocarbon fuel e.g. bromine and phosphorus as well as by lead and sulfur. In some reactor tests, operating on combat gasoline, lead poisoning of the nickel catalyst was suspected but not verified.

Migration of the nickel catalyst was observed in breadboard thermal cracker tests (see sect. 4.2.2). It is unknown whether this phenomenon is self-limiting, or could, with time, cause serious redistribution of catalytic activity within the bed.

### 5.2 Reactor Pressure Drop

Air pressure through the breadboard reactors was observed to vary from 12.5 to 15 inches of water during the burn-off cycle. Pressure drop through the ADM design reactors is predicted to be 10 inches of water. If a substantial reduction in pressure drop can be obtained by changes in reactor or catalyst geometry, reduction in blower size, weight and power consumption could be realized. This saving would be particularly beneficial during start-up as the cracker blower consumes more than two thirds of the start-up power requirements. Reduction of this power requirement would result in a smaller start-up battery and a lower battery charging load on the system.

### 5.3 Cracker Fuel-Air Control System

The cracker fuel-air control system as designed

### 5.3 Cont.

and tested on the breadboard system was an open loop system designed to maintain a constant carbon-oxygen ratio. An open loop system of this type requires a high degree of accuracy on all control and process elements to avoid cumulative errors. If a closed loop system could be developed in which carbon burn-off was controlled by a signal generated directly as a function of the completion of carbon burn-off the control system could be greatly simplified by eliminating the necessity for precise air and fuel metering. In a system of this type, the fuel pumps would be controlled by the fuel cell demand in a manner similar to that employed on the breadboard system and the blower would be controlled by the cracker-generated signal. Possible sources of the blower control signal are, air pressure drop, reactor temperature, and burn-off exhaust gas composition.

#### A. Air Pressure Drop

The decrease of flow resistance of the catalyst bed during carbon burn-off could be used as a burn-off control signal. A measurement of this, however, is complicated by catalyst settling during operation and handling and by the increase in flow resistance, caused by reactor temperature increases during burn-off.

#### B. Reactor Temperature

In an ideal reactor, blower shut-down could be initiated at the point of inflection of the catalyst bed temperature. This point of inflection occurs when carbon burn-off is completed and subsequent air serves only to cool the reactor. In an actual reactor detection of this point of inflection is difficult due to migration of the "hot" zone and changes of the CO-CO<sub>2</sub> formation ratio during the burn-off cycle.

#### C. Burn-Off Exhaust Gas Composition

During burn-off, the CO<sub>2</sub> composition of the cracker exhaust remains in the range of approximately 15 to 20% up to completion of burn-off. As complete carbon burn-off

### 5.3 Cont.

is approached the percentage of CO<sub>2</sub> in this stream drops precipitously. This decrease in CO<sub>2</sub> level can be detected by a relatively simple infrared cell.

### D. Recommendations

It is recommended that both reactor temperature and burn-off exhaust gas composition be further investigated as signal sources for a closed loop control system. Cracker temperature investigations should include integrated catalyst bed temperature e.g. a continuous resistance temperature element in the catalyst bed, as well as spot temperatures. Both the point of inflection and change of slope of the cracker temperature curve should be investigated as possible control points.

Burn-off exhaust gas composition should be monitored over the full range of fuel flow rates to determine if the CO<sub>2</sub> level can be used as a blower shut-off signal. CO<sub>2</sub> detection technique should also be investigated.

### 5.4 Fuel Cell Start-Up

For the ADM a fuel cell start-up system utilizing heat available from the thermal cracker was designed (see sect. 4.4.2). Operation of this system, however, has not been verified in actual testing. Prior to construction of the initial ADM performance of this system should be verified by breadboard test.

### 5.5 Fuel Cell Cost Reduction

Significant cost and weight savings can be realized by utilization of non-metallic bipolar plates and less expensive electrode structures. Graphite polar plates were investigated under this contract (see sect. 4) and it is anticipated that the ADM will employ carbon structure bipolar plates.

Simultaneously with work performed under this contract, Engelhard Industries has investigated low cost electrode

5.5 Cont.

structures under contract DAAK02-71-C-0297. Electrode improvements realized under this program will be incorporated into the ADM.

## 6.0 Conclusions and Recommendations

The work performed under this contract demonstrated that a practical power source can be realized through development of the open cycle fuel cell system. The breadboard test program confirmed fuel cell operation utilizing a hydrogen-rich fuel stream produced by thermally cracking logistic, military fuels. Further development is required, however, before a system suitable for field operation can be constructed.

Due to the advantages offered by the open cycle fuel system, such as silent operation, multi-fuel capability, reliability and fuel economy, Engelhard Industries recommends that this development be continued to allow full evaluation of the open cycle fuel cell power plant as a field power supply.



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## APPENDIX I

### Material Balance:

60 scfh of product gas containing an average of 75% H<sub>2</sub> will result in a Fuel Cell output of 1750 watts. Refer to Fig. 33.

### Basis:

1. Fuel Formula: C<sub>7.2</sub> H<sub>15.8</sub>
2. Fuel Consumption: 2.82 lb/hr = 0.0275 lb mole/hr
3. Cracker Cycle Time:
  - Purge: 1/2 minute
  - Cracking: 3 minutes
  - Burn-off: 2-1/2 minutes
4. Cracker product gas upstream of methanator contains 2% CO.
5. Hydrogen Utilization in Fuel Cell is 95%.
6. Hydrogen Consumption in Fuel Cell is 0.0375 gram/cell ampere - hour.
7. Volt/cell - 0.67.

### Calculations:

#### Fuel Consumption:

Purge: 0.42 lb/hr = 0.0040 lb. mole/hr  
Product Gas: 2.40 lb/hr = 0.0235 lb mole/hr  
Total 2.82 lb/hr = 0.0275 lb mole/hr

### Basic Reactions During the Cracking Cycle:

Purge: 0.00395 C<sub>7.2</sub> H<sub>15.8</sub> - 0.0206 H<sub>2</sub> + 0.0054 CH<sub>4</sub> = 0.023C  
Product Gas: 0.02355 C<sub>7.2</sub> H<sub>15.8</sub> - 0.1233 H<sub>2</sub> + 0.0314 CH<sub>4</sub> = 0.138C  
Total 0.02750 C<sub>7.2</sub> H<sub>15.8</sub> - 0.1439 H<sub>2</sub> + 0.0368 CH<sub>4</sub> = 0.161C

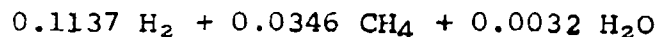
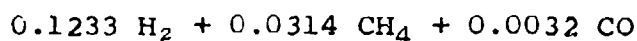
### Product Gas Upstream of Methanator:

Comp.	Lb/mole	SCFH	Vol%
H <sub>2</sub>	0.1233	46.6	78.0
CH <sub>4</sub>	0.0314	11.9	20.0
*CO	0.0032	1.2	2.0
C <sub>2</sub> H <sub>4</sub>	Trace	Trace	Trace
C <sub>2</sub> H <sub>6</sub>	Trace	Trace	Trace
N <sub>2</sub>	Trace	Trace	Trace
Total	0.1579	59.7	100.0

# APPENDIX I Cont.

\* Based on actual analysis performed, the average concentration of CO in the cracker product gas was taken as 2%.

## Methanation Reaction



## Feed Gas to Fuel Cell:

<u>Comp.</u>	<u>Lb/mole</u>	<u>SCFH</u>	<u>Vol. %</u>
H <sub>2</sub>	0.1137	43.0	75.0
CH <sub>4</sub>	0.0346	13.1	22.9
H <sub>2</sub> O	0.0032	1.2	2.1
C <sub>2</sub> H <sub>6</sub>	Trace	Trace	Trace
N <sub>2</sub>	Trace	Trace	Trace
Total	0.1515	57.3	100.0

The hydrogen utilization in the fuel cell is 95%.

## Fuel Cell Effluent Gas:

<u>Comp.</u>	<u>Lb/mole</u>	<u>SCFH</u>	<u>Vol. %</u>
H <sub>2</sub>	0.0057	2.15	13.1
CH <sub>4</sub>	0.0346	13.10	79.5
H <sub>2</sub> O	0.0032	1.20	7.4
C <sub>2</sub> H <sub>6</sub>	Trace	Trace	Trace
N <sub>2</sub>	Trace	Trace	Trace
Total	0.0435	16.45	100.0

## Hydrogen Used in the Fuel Cell:

$$0.1137 - 0.0057 = 0.1080 \text{ lb/mole/hr} = 0.216 \text{ lb/hr} = 40.8 \text{ scfh}$$

## Hydrogen Requirements to Produce 1750 Watts:

$$\frac{1750 \text{ Watt}}{0.67 \text{ Volt/Cell}} \times 0.005 \text{ gram H}_2/\text{Cell Ampere} \times \frac{1 \text{ lb}}{454 \text{ gram}}$$

$$= 0.216 \text{ lb H}_2/\text{hour} = 40.8 \text{ scfh}$$

APPENDIX I Cont.

ENERGY BALANCE (Refer to Fig. 33)

Energy Available:

$H_{R1}$ - Energy available from carbon combustion at 1800°F. Products of combustion at 1800°F.	18,200 Btu/hr
Energy available due to temperature decrease from 1800°F to 1200°F of cracker effluent gases during burn-off.	4,377 Btu/hr
Energy available due to temperature decrease from 1800°F to 300°F of cracker product gas.	2,079 Btu/hr
Energy available due to temperature decrease from 1800°F to 800°F of cracker purge gas.	251 Btu/hr
Total	24,907 Btu/hr

Energy Required:

$H_{R2}$ - Energy required for the fuel cracking reaction at 1800°F. Products of reaction are at 1800°F.	5,500 Btu/hr
$H_{R3}$ - Energy required for preheat of cracker product gas from 300°F to 600°F and for the methanation reaction at 600°F.	660 Btu/hr
Total	6,166 Btu/hr

Heat Losses:

$Q_1$  Loss = Energy loss from crackers and methanator envelope

$$Q_1 \text{ Loss} = H_{R1} - H_{R2} - R_3 = 24,907 - 6,166 = 18,741 \text{ Btu}$$

APPENDIX I Cont.

Energy Balance (Cont'd)

$Q_2$  loss = Energy loss from line between the methanator and fuel cell. The gases leave the methanator at 600°F and enter the fuel cell at 150°F.

$Q_2$  loss = 536 Btu/hr.



TABLE 10  
THERMAL CRACKER TESTING SUMMARY

CRACKER DWG.: SKA-15462-A NO.1, CATALYST LOADING DWG.: SKA-1546-B NO.1.  
CRACKER TYPE: STRAIGHT TUBE, FUEL TYPE: ESSO REGULAR

RUN #	DATE	CRACKER PREHEAT			FEED RATE		O/C	PRODUCT AVERAGE % H <sub>2</sub>	S.V. FEED SCFH CATALYST INLET	WATER OF CRACKER OUTSIDE WALL	CYCLE TIME			CUMULATIVE OPERATING TIME, HOURS	REMARKS
		BURNER TYPE	FUEL TYPE	RATE	FUEL	AIR					PURGE	CRACK	BURN OFF		
1	11/5/70	PT CATALYST IN CRACKER	H <sub>2</sub>	70 SCFH	2.5	240	1.5		1330	1800	1/2 MIN.	2 1/2 MIN.	3 MIN.		TEMP. PROTECTOR SHUT DOWN AT 1800°F
					1.75	168	1.5		931	1800				5 1/2	"
2	11/6/70	"	"	40 MIN	2.25	216	1.5	80.0	1197	1500	"	"	"		TEMP. PROTECTOR SHUT DOWN AT 2000°F
					1.67	256	2.4		889	1400					CATALYST PLUGGING
					1.67	172	1.6	80.0	889	1500				12	"
3	11/9/70	"	"	"	1.5	144	1.5	78.0	798	1950	"	"	"	15	"
4	11/11/70	"	"	"	1.5	144	1.5	82.0	798	1800	"	"	"	18	CRACKER PLUGGED ON 11/11/70

TABLE II

## THERMAL CRACKER TESTING SUMMARY

CRACKER DWG.: SKA-15463-B NO 2 CATALYST LOADING DWG.: B-15603 NO 2  
 CRACKER TYPE: DIP TUBE - CATALYST IN DIP TUBE FUEL TYPE: COMBAT GASOLINE

RUN #	DATE	CRACKER PREHEAT			FEED RATE			PRODUCT		% H <sub>2</sub>		S. V.	MAX. TEMP. °F			CYCLE TIME MINUTES		Δ P IN INCH. W.C. THRU CRACKER		CLIMATE OPERATING TIME, HOURS	REMARKS		
		BURNER TYPE	FUEL TYPE	AIR FLOW RATE SCFH	FUEL RATE LB/Hr	AIR SCFH	OIL SCFH	AV. FLOW RATE, H <sub>2</sub> SCFH	EFFIC.	H <sub>2</sub> FEED TUBE SCFH	H <sub>2</sub> IN PROCESS H <sub>2</sub> IN FEED		H <sub>2</sub> FEED TUBE SCFH	DIP CATALYST AT OUTER TUBE INNER WALL	PURGE CATALYST BURN OFF	PRE-BURN OFF HEAT SAVING	END						
5	11/27/70	CRACKER IN DEOXO	H <sub>2</sub>	90	630	60	1.5	144	1.5	70		798	1650	1900	1/2	2 1/2	3			5 1/2	NO CATALYST PLUGGING		
6	11/27/70	"	"	"	"	"	1.5	163	1.7	70		798	1650	2000	"	"	"			8 1/2	6 1 1/2	"	
7	11/23/70	"	"	"	"	"	1.5	154	1.6	72		798	1750	2150	"	"	"			11 3/4	7 1/8	16	SLIGHT CATALYST PLUGGING
8	11/24/70	"	"	"	"	"	1.5	154	1.6	73		798	1780	2200	"	"	"				22	22	THERMO-WELL IN CATALYST BED BURNED
9	11/25/70	"	"	"	"	"	1.5	154	1.6	75		798	1550	2000	"	"	"			29 10 3/4	8	27	NO CATALYST PLUGGING



TABLE 12

## THERMAL CRACKER TESTING SUMMARY

CRACKER DWG.: 3-15577 NO.3 CATALYST LOADING DWG.: 8-15590 NO.3  
 CRACKER TYPE: DIP TUBE - CATALYST IN DIP TUBE FUEL TYPE: COMBAT GASOLINE  
 CYCLE TIMES: PURGE - 1/2 MIN., CRACKING - 2 1/2 MIN., BURN OFF - 3 MIN.

RUN #	DATE	CRACKER PREHEAT						FEED RATE		PRODUCT		% H <sub>2</sub>	S.V.	INT. TEMP. OF CRACKER	OP. THRU CRACKER	CUMULATIVE OPERATING TIME, HOURS	REMARKS					
		BURNER TYPE	FUEL TYPE	AIR RATE SCFH	FUEL RATE lb/hr	AIR SCFH	O/C	AV. FLOW % H <sub>2</sub>	RATE % H <sub>2</sub>													
										TYPE	RATE SCFH							TEMP °F	WALL	PRE-HEAT	BURN OFF START	END
10	11/30/70	PL. CATALYST IN DEOXY	H <sub>2</sub>	90	630	60	1.94	200	1.5	73		1332	1650				CATALYST PLUGGING					
"	"	"	"	"	"	"	1.5	200	1.9	75	34	65.0	798	1670	28	10 3/4	8	NO CATALYST PLUGGING				
11	12/1/70	"	"	"	"	"	1.5	163	1.7	75		798	1620		11	8 1/4						
"	"	"	"	"	"	"	2.0	205	1.6	73	48.6	68.0	1064	1830		12	8 1/2	11 3/4	SLIGHT CATALYST PLUGGING AT 9°C. 1.6. NO PLUGGING AT 9.17			
12	12/2/70	"	"	"	"	"	0.7	76	1.7	70		371	1300		3	2 1/2	16 1/2	NO CATALYST PLUGGING				
13	12/3/70	"	H <sub>2</sub>	70	590	46	2.5	272	1.7	68		1330	1970	18 1/2	17 1/2	10 1/2	20	"				

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TABLE 13

## THERMAL CRACKER TESTING SUMMARY

CRACKER DWG: B-15568 NO.4 (RUN # 14 THROUGH RUN # 20)

CATALYST LOADING DWG: B-15575 NO.4 (RUN # 14 THROUGH RUN # 16), B-15584 NO.5 (RUN # 17 THROUGH RUN # 20)

CRACKER TYPE: DIPTUBAF. CATALYST IN DIPTUBE FUEL TYPE: JP-4

RUN DATE	CRACKER PREHEAT FUEL AIR	PRODUCT % H <sub>2</sub>	EFFIC. %	H <sub>2</sub> FEED, DIP TUBE DEPT. OUTER INNER	CATALYST CU. FT. WALL	TEMP. OF	INCH. W.C. THRU CRACKER	CUMULATIVE OPERATING TIME	REMARKS
#	TYPE	TIME RATE	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT	PERCENT
14 12/28/70	Pt/Rh RESISTOR JP-4 WIRE	2.462	12	1.5	350	1.8	798	1620	2000
15 12/29/70	"	2.462	25	1.5	350	1.878	34	67.5	792
16 12/30/70	"	2.558	24	1.5	350	1.878	34	67.5	792
17 1/4/71	"	2.462	23	0.8	350	2.076	20	72.5	445
18 1/5/71	"	2.558	25	2.8	350	2.076	21	76.0	445
19 1/6/71	"	2.558	17	1.6	350	1.771	38	70.8	390
20 1/7/71	"	2.558	16	2.5	350	1.6		1385	1790

<sup>1</sup> CYCLE TIME: PURGE - 1/2 MIN., CRACKING - 3 MIN., BURN OFF - 1 3/4 MIN., WAIT - 3/4 MIN.<sup>2</sup> CYCLE TIME: PURGE - 1/2 MIN., CRACKING - 3 MIN., BURN OFF - 1 MIN., WAIT - 1 1/2 MIN.<sup>3</sup> CYCLE TIME: PURGE - 1/2 MIN., CRACKING - 3 MIN., BURN OFF - 2 1/2 MIN., WAIT - 0 MIN.

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TABLE 14

## THERMAL CRACKER TESTING SUMMARY

CRACKER DWG.: B-15616 NO.5, CATALYST LOADING DWG.: S-15617 NO.6

CRACKER TYPE: DIP TUBE - CATALYST IN DIP TUBE, FUEL TYPE: JP-4

RUN DATE #	CRACKER PREHEAT			FEED RATE		PRODUCT		% H <sub>2</sub> EFFIC. H <sub>2</sub> in PROD. H <sub>2</sub> in FEED	S.V. H <sub>2</sub> FEED SCFH CATALYST CU. FT.	MAX. TEMP. OF DIP TUBE OUTER PURGE WALL	CYCLE TIME, MINUTES		CUMU- LATIVE OPERATING TIME, HOURS	REMARKS
	BURNER TYPE	FUEL TYPE	AIR RATE SCFH	FUEL RATE lb/hr.	AIR RATE SCFH	Q. C	AV. FLOW RATE, H <sub>2</sub> SCFH				ON	OFF		
21 1/12/71	PL/Rh RESISTO WIRE		350	1.6	350	1.7	70		890	1550	1 1/2	3 13/4	7 1/2	NO CATALYST PLUGGING
22 1/12/71	"	"	"	1.6	350	1.7	76	70.8	890	1550	"	"	16 1/2	"
23 1/19/71	"	"	"	1.6	350	1.7	78	72.6	890	1550	"	"	24	"
24 1/20/71	"	"	"	2.0	350	1.8	75	69.0	1120	1690	1 1/2	3 21/3	31	"
25 1/21/71	"	"	"	2.4	350	1.7	75	69.2	1340	1740	1 1/2	3 21/2	37	"

TABLE 15

## THERMAL CRACKER TESTING SUMMARY

CRACKER DWG.: B-15610 NO.6 (RUN#26 & 27), B-15637 NO.7 (RUN#28, 29 & 30), B-15705 NO.8 (RUN#31 THRU RUN#38)  
 CATALYST LOADING AND CRACKER ASSY DWG.: B-15614-A NO.7 (RUN#26), B-15708 NO.8 (RUN#27), B-15638 NO.9  
 (RUN#28, 29 & 30), B-15706 NO.10 (RUN#31), B-15707 NO.11 (RUN#32 THRU RUN#38)

CRACKER TYPE: DIPTUBE - CATALYST IN THE ANNULUS

RUN #	DATE	CRACKER PREHEAT			FEED			PRODUCT		% H <sub>2</sub> EFFIC.	S.V. H <sub>2</sub> FEED SCFH	MAX. TEMP OF CATALYST (W. FT.)	CYCLE TIME, MINUTES			ΔP THRU CRACKER IN INCH. W.G.	CUMULATIVE OPERATING TIME, HOURS	REMARKS		
		BURNER TYPE	FUEL RATE	AIR RATE	FUEL TYPE	RATIO	AIR SCFH	O	C				AV. FLOW % H <sub>2</sub> SCFH	PURE CRACKER	BURN OFF TIME, HRS				PRE HEAT	
26	1/25/71	PURE COMB. FUEL W/RE GAS	1.0	2.34	30	1.3	350	1.84			679	1900	2200	1	3	1 1/2	3 1/2	PLUGGING CATALYST IN PROD. GAS		
27	1/29/71	"	"	"	"	1.3	"	1.84	75	29	7	1900	2200	"	"	"	7 4	"		
28	2/11/71	"	"	"	22	1.25	"	1.92				1700		"	"	"	2 1/2	"		
29	2/16/71	"	"	"	20	1.0	"	2.24	75		555	1750		1 1/2	2 3/4	1 1/4	8 5 1/2	"		
30	2/17/61	"	1.75	40	17	"	1.0	1.8	78	22	555	1600		1 1/2	3	1 1/2	18	NO PLUGGING CATALYST IN PROD. GAS		
31	2/18/71	JP-4	1.75	40	19	"	1.0	1.8	80	23	552	1700		"	"	"	7 6 1/2	"		
32	2/19/71	"	"	"	"	1.9	"	1.75	78		1050	2000	1/2	2 3/4	2	2 3/4	8 6 3/4	NO PLUGGING CATALYST IN PROD. GAS		
33	2/22/71	"	"	"	18	"	2.6	"	1.6	75	1440	2000	1/2	2 3/4	2 1/2	1 1/2	12 11	"		
34	2/24/71	"	2.5	58.5	12	"	1.0	2.24	82		552	1700	1/2	2 3/4	1 1/2	1 1/4	9 4 1/2	NO PLUGGING CATALYST IN PROD. GAS		
35	2/25/71	"	"	"	11	"	2.0	1.7	77		1104	1950	1/2	2 3/4	2	2	9	52	NO PLUGGING CATALYST IN PROD. GAS	
36	2/26/71	"	"	"	11	"	2.0	1.7	78		1104	1500	"	"	"	"	9 10 1/2	56	NO PLUGGING CATALYST IN PROD. GAS	
37	3/1/71	"	2.5	69	14	"	2.5	1.76	75		1350	1600	1/2	2 3/4	2 1/2	1 1/2	13 1/2	62	"	
38	3/2/71	"	2.5	58.5	10	"	2.5	1.76	78	60	1350	1500	"	"	"	"	9 15	12 1/2	71	"

**TABLE 16**  
**SYSTEM TESTING SUMMARY**

CRACKER DWG.: B-15687 NO.9 (RUN #39 THRU 50 & 52A) B-15788 NO.10 (RUN #51 THRU 54)

CATALYST LOADING DWG.: B-15688 NO.12 (RUN #39 THRU 50 & 52A) B-15789 NO.13 (RUN #51 THRU 54)

CRACKER TYPE: DIP TUBE - CATALYST IN THE ANNULUS

RUN #	DATE	FEED			PRODUCT			% H <sub>2</sub> EFFIC	S.V. PMA	AP, INCH-WG. THROUGH CRACKER AND VALVES	FUEL CELL OUTPUT			REMARKS				
		FUEL TYPE	FUEL RATE	AIR RATE	O.C.	AV. %	FLOW RATE, SCFH				H <sub>2</sub> FEED OF OTHER PRE	BURN OFF	START TIME		END TIME	VOLT	AMP	WAT.
39	3/6/77	CONG GAS	1.5	350	1.6			352	1720	6 1/2	6	4 1/2				NO CARBON IN PRODUCT GAS		
"	"	"	1.25	350	1.92			294	1500	6 1/2	5 1/2	4	3			"		
40	3/11/77	"	1.25	350	1.92	76		294	1500	6 1/2	4 1/2	4	10			NO CARBON IN PRODUCT GAS		
41	3/11/77	"	1.25	350	1.92	78		294	1500	6 1/2	5 1/2	4	20 1/2			"		
42	3/11/77	"	2.0	350	1.6			469	1500	6 1/2			24			CARBON IN PRODUCT GAS, NO PLUGGING		
"	"	"	1.5	350	2.13			352	1500		7 1/2	6 1/2	26 1/2			NO CARBON IN PRODUCT GAS, NO PLUGGING		
43	3/22/77	"	1.5	296	1.8	76		352	1500		8 1/2	7 1/2	30			NO CARBON IN PRODUCT GAS, NO PLUGGING		
44	3/23/77	"	1.5	287	1.7	78		352	1500				36			"		
45	3/24/77	"	1.5	280	1.7			352	1500				30 1/2	3	40	320	"	
46	3/24/77	"	1.5	275	1.65			352	1500				44			"		
47	3/31/77	"	1.5	305	1.85	80		352	1500							CARBON IN PRODUCT GAS, NO PLUGGING		
"	"	"	1.25	256	1.86	82		294	1500		3 1/2	3 1/4	51	3	32	202	NO CARBON IN PRODUCT GAS, NO PLUGGING	
48	3/31/77	"	1.25	256	1.86	84		294	1500		3 1/2	3	55	8	34	231	"	
49	4/7/77	"	1.25	256	1.86	84		294	1500		3 1/2	3	62 1/2	13	22	205	"	
50	4/11/77	"	1.25	256	1.86	84		294	1500		3 1/2	3 1/2	72 1/2	8	20	206	"	
51	4/11/77	"	1.25	265	1.92			371	1500				4 1/2			"		
53	4/15/77	"	1.25	265	1.92			371	1500				13			"		
52A	4/15/77	"	1.25	265	1.92	82	31	26	65.4	294	1500	5 1/2	5	81			NO CARBON IN PRODUCT GAS, NO PLUGGING	
53	4/19/77	"	1.25	350	1.7			371	1600	2	8	6				"		
"	"	"	1.75	350	1.8			371	1650		9	7				CARBON IN PRODUCT GAS, NO PLUGGING		
"	"	"	2.5	350	1.6			742	1700		10	8	21			CARBON IN PRODUCT GAS, NO PLUGGING		
54	4/20/77	"	2.5	350	1.6			742	1700		12	10	24 1/2			"		

**NOTES**

1. CRACKER PREHEAT : A Pt/Pt RESISTOR WIRE USED TO PREHEAT THE FUEL. THE PRE-HEAT TIME VARIED FROM 10 MIN. TO 12 MIN.

2. CYCLE TIME PURGE - 1/2 MIN. CRACKING - 3 MIN. BURN OFF - 2 1/2 MIN OR LESS

3. FUEL CELL : PRODUCT GAS (RUN # 45, 47, 48, 49 & 50) INTRODUCED TO 400 WATT FUEL CELL. H<sub>2</sub> UTILIZATION VERY POOR DUE TO OLD AGE (> 3000 HOURS) OF FUEL CELL.

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TABLE 17

## SYSTEM TESTING SUMMARY (1.75 KW FUEL CELL)

CRACKER DWG: B-15790 NO. 11, CATALYST LOADING AND CRACKER ASSY: B-15791 NO. 14

CRACKER TYPE: DIPTUBE - CATALYST IN THE ANNULUS FUEL TYPE: CRBAT GASOLINE, EXCEPT IN RUNS # 57, 58 &amp; 59 - JPM

RUN #	D	CRACKER PREHEAT				FEED RATE		PRODUCT			% H <sub>2</sub> EFF.	S.V. MAX. TEMP. OF SHELL, OUTLET CUFF WALL	CUMULATIVE OPERATING TIME, HOURS	FUEL CELL OUTPUT		REMARKS	
		CRACKER TYPE	FUEL TYPE	FUEL RATE (LBS/H)	AIR RATE (LBS/H)	Q	C	AV. RATE (LBS/H)	% H <sub>2</sub>	FLOW RATE (LBS/H)				SYSTEM	WATT		
55	4/24/74	"	"	1.5	510	15	125	350	17		630	1700	9			CARBON IN PRODUCT GAS, NO PLUGGING	
56	4/24/74	"	"	2.0	462	10	175	350	17		630	1700	17 1/2			"	
57	4/24/74	"	"	2.0	462	10	125	350	17		630	1600	2 1/2	2	25 32	800	NO CARBON IN PRODUCT GAS, NO PLUGGING
58	4/24/74	"	"	"	"	"	10	125	350	17		630	1600	9 1/2	25 32	800	"
59	4/24/74	"	"	"	"	"	10	2.5	350	16	76	1260	1650	33	28 43	300	"
60	5/5/74	"	"	2.5	524	10	2.5	350	16	76		1260	1650	35			"
61	5/14/74	"	"	2.5	524	10	2.5	350	16	77		1260	1650	38 1/2	27 42	1234	"
62	5/14/74	"	"	2.5	524	9	2.5	350	16	76		1260	1650	41	27 42	1234	"
63	5/14/74	"	"	2.5	524	10	2.5	350	16	75		1260	1650	44	28 43	1300	"
64	5/14/74	"	"	2.5	524	10	2.5	350	16	75		1260	1650	49	26 40	1140	"
65	5/14/74	"	"	2.5	524	10	2.5	350	16			1260	1670	53 1/2			"
66	5/14/74	"	"	2.5	524	8	2.5	350	16	76		1260	1670	59	27 42	1234	"
67	5/14/74	"	"	2.5	524	9	2.5	350	16	77		1260	1670	63	27 42	1234	"
68	5/14/74	"	"	2.5	524	9	2.5	350	16	76		1260	1670	70	27 42	1234	"

## NOTES:

\* THE FUEL CELL POWER OUTPUT (WATTS) INCLUDES THE FUEL CELL BLOWER POWER REQUIREMENTS

CYCLE TIME: PURGE - 1 MIN, UNLOADING - 3 MIN, BURN OFF - 2 1/2 MIN. OR LESS